EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

2-1. Purpose.

The following examples show the use of design procedures explained in the previous section:

- 2-2 Steel fuel oil lines
- 2-3 Underground storage tanks
- 2-4 On-grade tank bottoms
- 2-5 Gas distribution systems
- 2-6 Elevated water tanks (ice is expected)
- 2-7 Elevated water tanks (no icing will occur)
- 2-8 On-grade water storage reservoir (ice is expected)

2-2. Steel Fuel Oil Lines.

Impressed current cathodic protection is desired for the 6-in. welded fuel oil line shown in figures 2-1A and 2-lB. Since this pipeline is in existence, current requirement tests have already been made. There are no other underground structures in the area, so a surface point groundbed is chosen. Figure 2-2 illustrates a surface point groundbed anode system using prepackaged ceramic rod anodes. These prepackaged ceramic rod anodes are further detailed in figures 2-3 and 2-4.

a. Design data.

1) Soil resistivity in area where groundbed is desired is 2000 ohm-cm.

2) Pipe has 6-in. diameter (outside diameter = 6.625 in.)

3) Pipe length is 6800 ft.

4) Design life for cathodic protection anodes is 15 years since the structure will no longer be needed after that time.

5) Design current density is 2-mA per sq ft of bare pipe.

6) The pipe is coated with hot-applied coal-tar enamel.

7) 90 percent coating efficiency based on previous experience with this type coating.

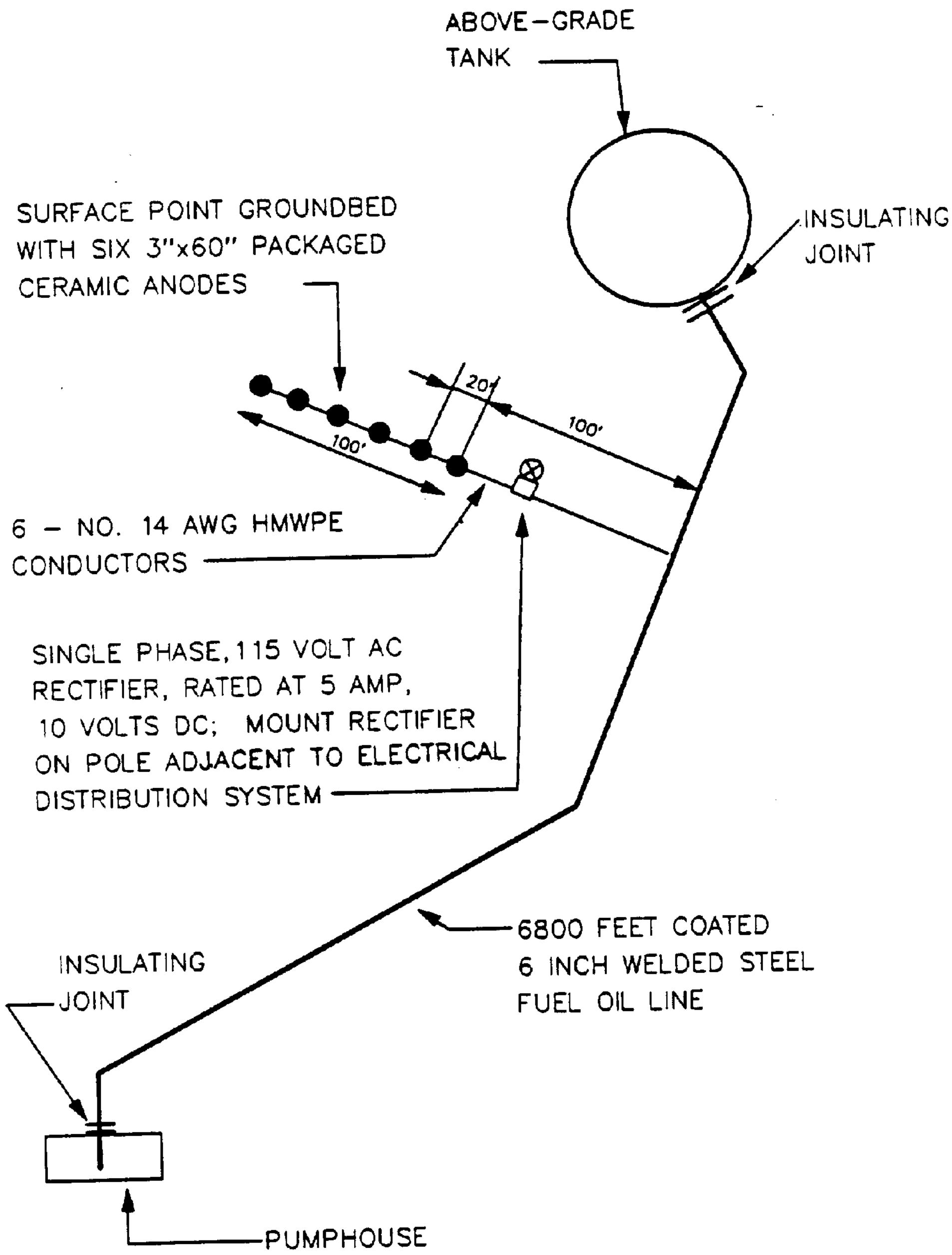


Figure 2-1A Cathodic Protection System for Fuel Oil Line With Anode Bed Extended Perpendicular From Pipeline

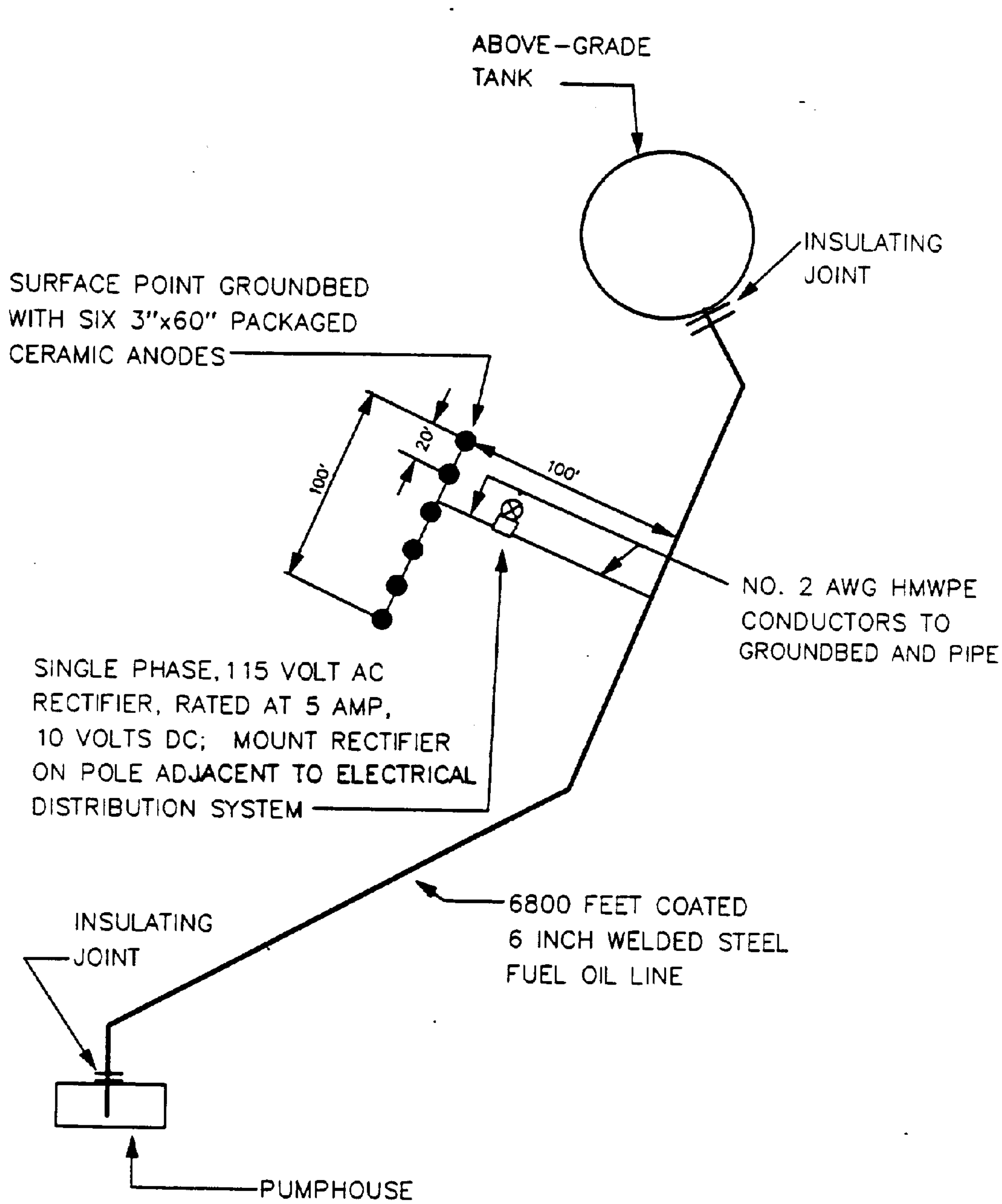


Figure 2-1B Cathodic Protection System for Fuel Oil Line With Anode Bed Installed Parallel to Pipeline

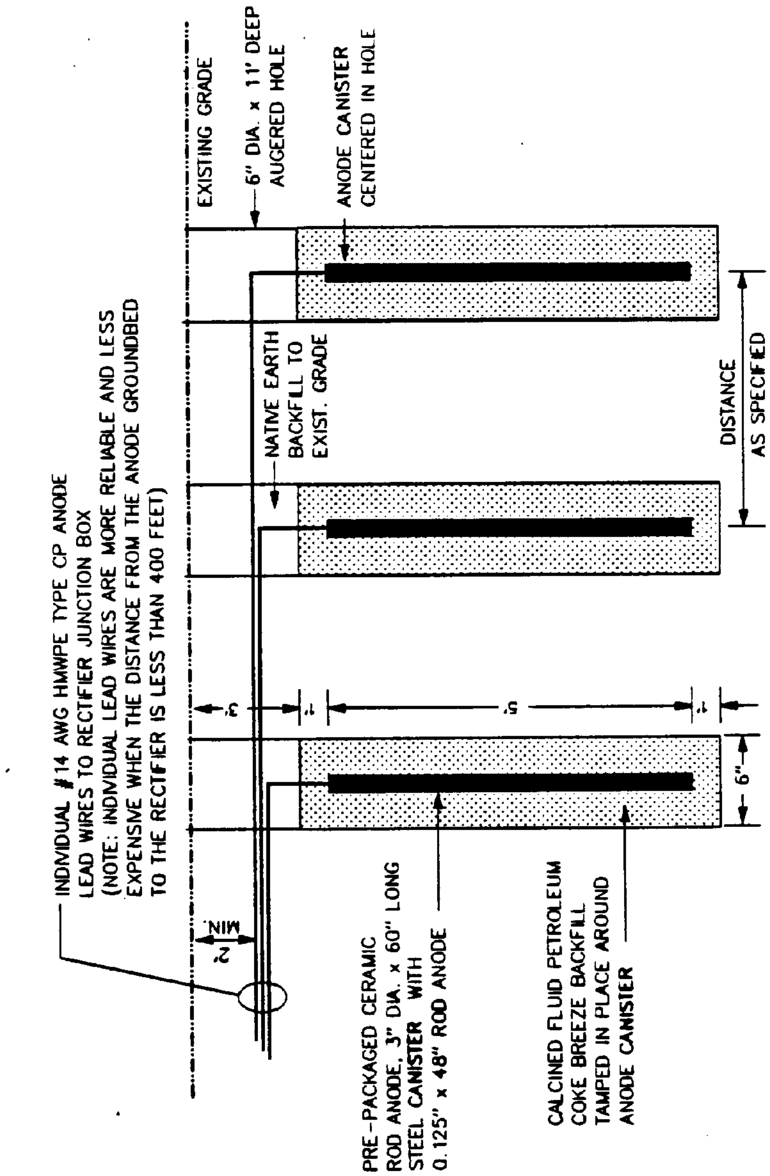


Figure 2-2 Vertical Groundbed Layout Using Prepackaged Ceramic Rod Anode

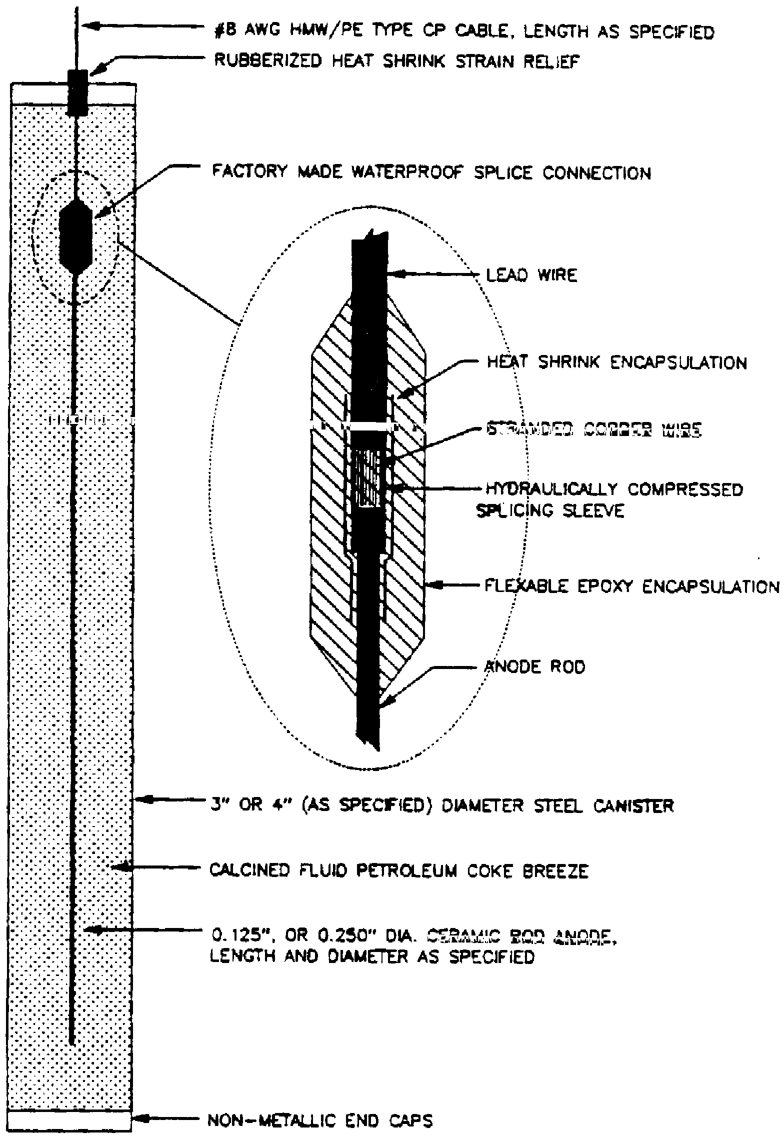


Figure 2-3 Prepackaged Ceramic Rod Anode for Underground Use

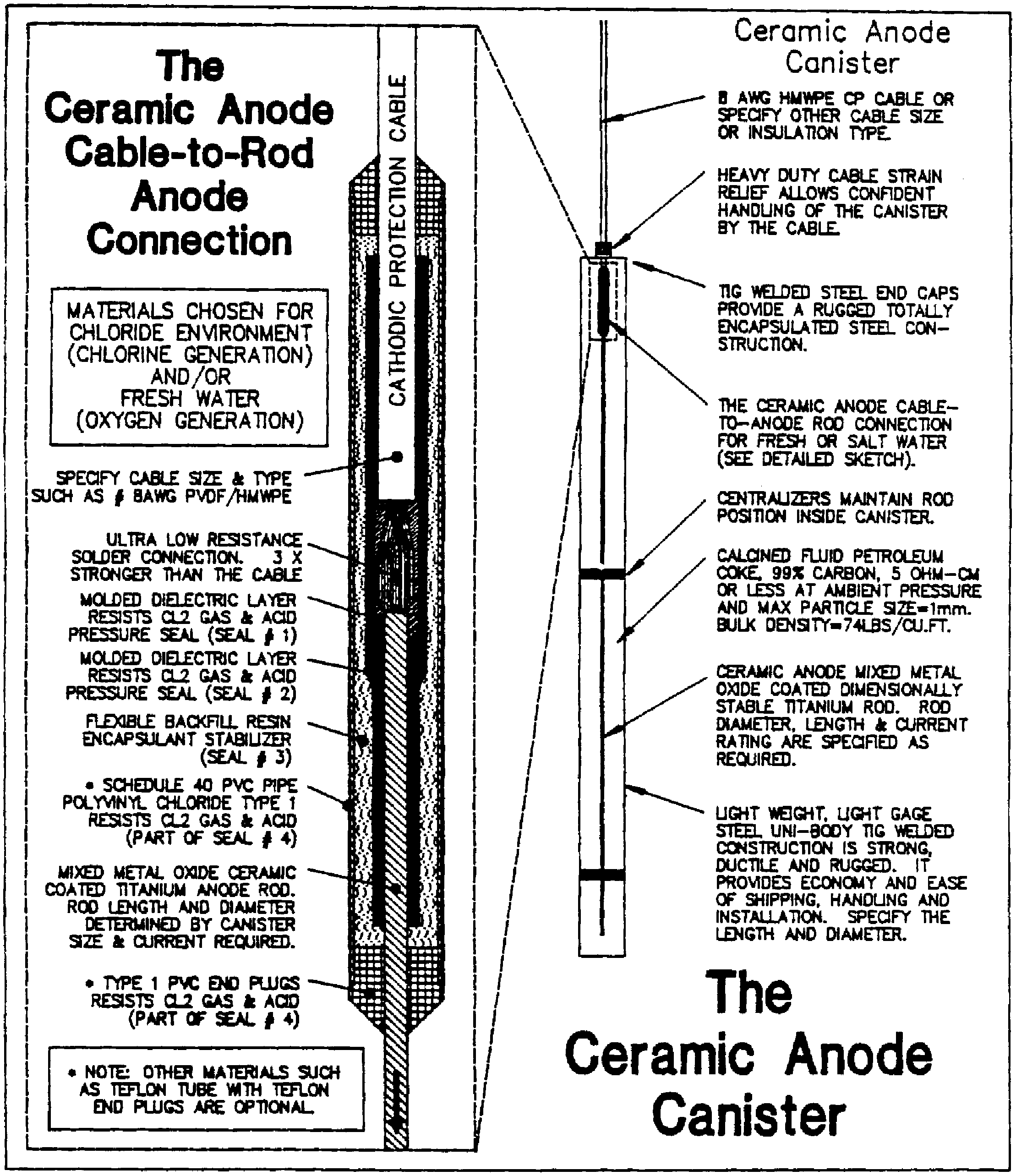


Figure 2-4 Ceramic Anode Canister Prepackaged Rod

8) Effective coating resistance at 15 years is estimated at 2500 ohm-sq ft.

9) The pipeline is isolated from the pumphouse and tank with insulating joints.

10) For this example, we have decided that the cathodic protection system circuit resistance should not exceed 2.5 ohms.

11) Electric power is available at 120/240 V single phase AC from a nearby overhead distribution system.

12) Current requirement testing indicates that 2.8 amp are needed for adequate cathodic protection.

b. Computations.

1) Calculate the external surface area of the pipe.

Pipe diameter	=	6 in.
Pipe length	=	6800 ft
Pipe surface area per lin ft	=	1.734 sq ft/lin ft (from table 3-2)
External pipe surface area	=	6800 lin ft x 1.734 sq ft/lin ft = 11,791 sq ft

2) Check the current requirement (I) using equation 1-1:

$$I = (A)(I')(1.0 - C_E)$$

Where:

A = 11,791 sq ft - External pipe surface area from previous calculation.

I' = 2 mA/sq ft - Required current density from item 5 of paragraph 2-2a.

C_E = 0.90- Coating efficiency expressed in decimal form from item 7 of paragraph 2-2a.

I = 11,791 sq ft x 2 mA/sq ft x (1.0 - 0.90)

$I = 2358$ mA or approximately 2.4 amp

which agrees well with the current requirement test data provided in item 12 of paragraph 2-2a.

3) Select an anode and calculate the number of anodes required (N) to meet the design life requirements. Two sizes are selected for trial calculations using equation 1-2:

$$N = \frac{I}{I_A}$$

Where:

I = 2.8 amp (Current requirement from item 12 of paragraph 2-2a)

I_A = Current rating per anode, varies depending on anode size from table 3-3.

Several different size anodes could be chosen. Experience has shown that for this type of groundbed, 60-in. long anode packages are desirable.

For a 3-in. by 60-in. packaged canisters with a 1/8-in. by 48-in. ceramic anode rod, I_A = 1.2 amp/anode (from table 3-3 for 15-year design life).

$$N = \frac{2.8}{1.2} = 2.33\text{; use 3 anodes.}$$

For a 3-in. by 60-in. packaged canister with a 1/4-in. by 48-in. ceramic anode rod, I_A = 2.4 amp/anode (from table 3-3 for a 15-year design life).

$$N = \frac{2.8}{2.4} = 1.17\text{; use 2 anodes.}$$

4) Calculate the resistance of a single anode-to-earth (R_A) from equation 1-6:

$$R_A = \frac{p\,K}{L}$$

Where:

p = 2000 ohm-cm (Soil resistivity in area where groundbed is desired from item 1 of paragraph 2-2a)

K = 0.0213 (Shape function, from table 3-4 [where: L/d = 60 in./3 in. = 20])

L = 5 ft (Effective anode length [canister length))

d = 3 in. (Anode backfill diameter [canister diameter])

$$R_A = \frac{2000 \times 0.0213}{5}$$

R_A = 8.53 ohms

5) Calculate the number of anodes required to meet maximum anode groundbed-to-earth resistance requirements from equation 1-11:

$$R_N = \frac{R_A}{N} + \frac{p\, P_F}{C_C}$$

Where:

R_N = Groundbed-to-earth resistance.

R_A = 8.53 ohms (Resistance of a single anode-to-earth from the previous calculation)

N = Assume 5 anodes (discussed below)

p = 2000 ohm-cm (Soil resistivity)

P_F = 0.00268 (Paralleling factor from table 3-5 [discussed below])

C_C = 20 ft (Center-to-center spacing of anodes [discussed below])

To determine P_F, a figure for N must be assumed. This paralleling factor compensates for mutual interference between anodes and is dependent on spacing. From the law of parallel circuits, it appears that five anodes might give the desired circuit resistance of 2.0 ohms maximum, i.e.:

$$\frac{8.53 \text{ ohms/anode}}{5 \text{ anodes}} = 1.706 \text{ ohms}$$

This is the approximate resistance based on the law for parallel circuits. (When equal resistance values are joined together in a parallel circuit, the total resistance value of the circuit is approximately equal to a single resistance value divided by the number of resistance values.)

To calculate the true anode resistance for five anodes, we must perform the calculation from equation 1-11.

C_C = 20 ft (The spacing must be chosen based on previous experience to solve the equation.) The spacing can typically be from 10 to 50 ft. For this example, we will try 20 ft:

$$R_N = \frac{8.53}{5} + \frac{2000 \times 0.00268}{20}$$

$$R_N = 1.706 + 0.268$$

$$R_N = 1.974 \text{ ohms}$$

This is within specification, but very close to exceeding maximum specified circuit resistance. Try six anodes to allow for variations in soil resistivity and to allow for wire and pipe-to-earth resistance. Repeat calculation from equation 1-li,

Where:

N = 6 anodes

P_F = 0.00252, paralleling factor from table 3-5

$$R_N - \frac{8.53}{6} + \frac{2000 \times 0.00252}{20}$$

$$R_N = 1.67 \text{ ohms}$$

6) Based on the previous selection of six anodes for the number of anodes to be used, the total circuit resistance must be determined.

7) Select an area for anode bed placement. Here, the selected area is 100 ft from the pipeline for improved current distribution. The anode bed location for this type design must be far enough away from the structure

to be protected to assure uniform distribution of the protective current to all structure components. The higher the soil or water resistivity, the further away the ground must be located. For this example, previous experience has shown that the nearest anode should be located a minimum of 100 ft from the structure to assure good current distribution. Since there are no other underground utilities in the area, the groundbed may be installed either perpendicular or parallel to the pipe (figures 2-IA and 2-lB).

8) Determine the total circuit resistance (R_T) from equation 1-3:

$$R_T = R_N + R_W + R_C$$

Where:

R_N = Groundbed resistance-to-earth (ohms)
R_W = Header cable and resistance (ohms)
R_C = Pipe-to-earth resistance (ohms)

a) Groundbed-to-earth resistance (R_N) from step 5.

R_N = 1.67 ohms

Specify anodes with individual lead wires of sufficient length so that each anode wire can be run directly to the rectifier without splices. (This is virtually always true for anode bed designs where the individual lead wire lengths required do not exceed an average of 400 ft.)

b) Anode lead wire resistance from equation 1-15:

c

$$R_W = \frac{L_W \, R_{MFT}}{1000 \text{ ft}}$$

Where:

L_{AVG} = Total of each actual lead wire lengths/number of anodes
= (140 ft + 120 ft + 100 ft + 80 ft + 60 ft + 40 ft)/6 anodes
= 90 ft per anode

L_W = L_{AVG}/N
= 90/6
= 15 ft

= Average anode lead wire length/number of anodes. This is based on the circuit resistance for 6 anode lead wires in parallel.

R_{MFT} = 2.58 ohms - Resistance for No. 14 AWG cable which has been selected from table A-6.

$$R_W = \frac{15 \text{ ft} \times 2.58 \text{ ohms}}{1000 \text{ ft}}$$

R_W = 0.039 ohms

c) Pipe-to-earth resistance (R_C) from equation 1-16:

$$R_C = \frac{R_S}{A}$$

Where:

R_S = 2500 ohm-sq ft - Effective coating resistance from item 8 of paragraph 2-2a.

A = 11,791 sq ft - External pipe surface area calculated in step 1 of paragraph 2-2b.

$$R_C = \frac{2500 \text{ ohm-sq ft}}{11{,}791 \text{ sq ft}}$$

R_C = 0.212 ohm

d) Calculate the total circuit resistance (R_T) from equation 1-3:

$R_T = R_N + R_W + R_C$

$R_T = 1.67 + 0.039 + 0.212$

R_T = 1.921 ohms

e) Since the design requirements call for a maximum allowable groundbed resistance of 2.0 ohms and R_T = 1.921 ohms, the design using six (3-in x 5-ft) ceramic anode canisters will work.

9) Calculate the rectifier voltage (V_{REC}) from equation 1-17:

$$V_{REC} = (I)\ (RT)\ (120\%)$$

Where:

I	=	2.8 amps (Current requirement from item 12 of paragraph 2-2a.
R_T	=	1.92 ohms (Total circuit resistance from previous calculation.
120%	=	Rectifier voltage capacity design safety factor.
V_{REC}	=	2.8 amp x 1.92 ohms x 1.2
V_{REC}	=	6.45 V

c. Select rectifier.

Based on the design requirement of 2.8 amperes and 6.45 volts, specify a 10-V, 5-amp rectifier, which is the nearest standard capacity available from commercial cathodic protection rectifier manufacturers.

2-3. Underground Storage Tanks (USTs).

The service station shown in figure 2-5 has three existing underground tanks and associated pipe. The quality of the coating is unknown and it is not feasible to install dielectric insulation to isolate the UST system. Because of the anticipated large current requirement, an impressed current protection system is chosen. To distribute the current evenly around the tanks and piping, and to minimize interference effects on other structures, a distributed anode surface bed using vertical anodes is selected. Vertical anodes can be installed with relative ease in holes cored through the paving around the UST system. Wiring can be installed several inches below the paving by cutting and hand excavating narrow slots/trenchs through the paving.

a. Design data.

1) Soil resistivity is 4500 ohm-cm.

2) Pipe is 2 in., nominal size. Total length of all buried piping is 750 ft.

3) Tanks are 8000 gal, 96 in. diameter by 21 ft 3 in. long.

4) Electrical continuity of tanks and piping has been assured.

5) It is not feasible to install dielectric insulation; system is therefore not isolated electrically from other structures.

6) Design cathodic protection anodes for 20-year life.

7) Coating quality is unknown, assume bare.

8) The cathodic protection system circuit resistance should not exceed 2.5 ohms.

9) Electric power is available at 120 V single phase in the station building.

10) Current requirement test indicates that 8.2 amperes are needed for cathodic protection.

b. Computations.

1) Find the external surface area (A) of the storage tanks and piping.

Area of each tank = 2 B (tank radius)^2 + B (tank diameter) (tank length)

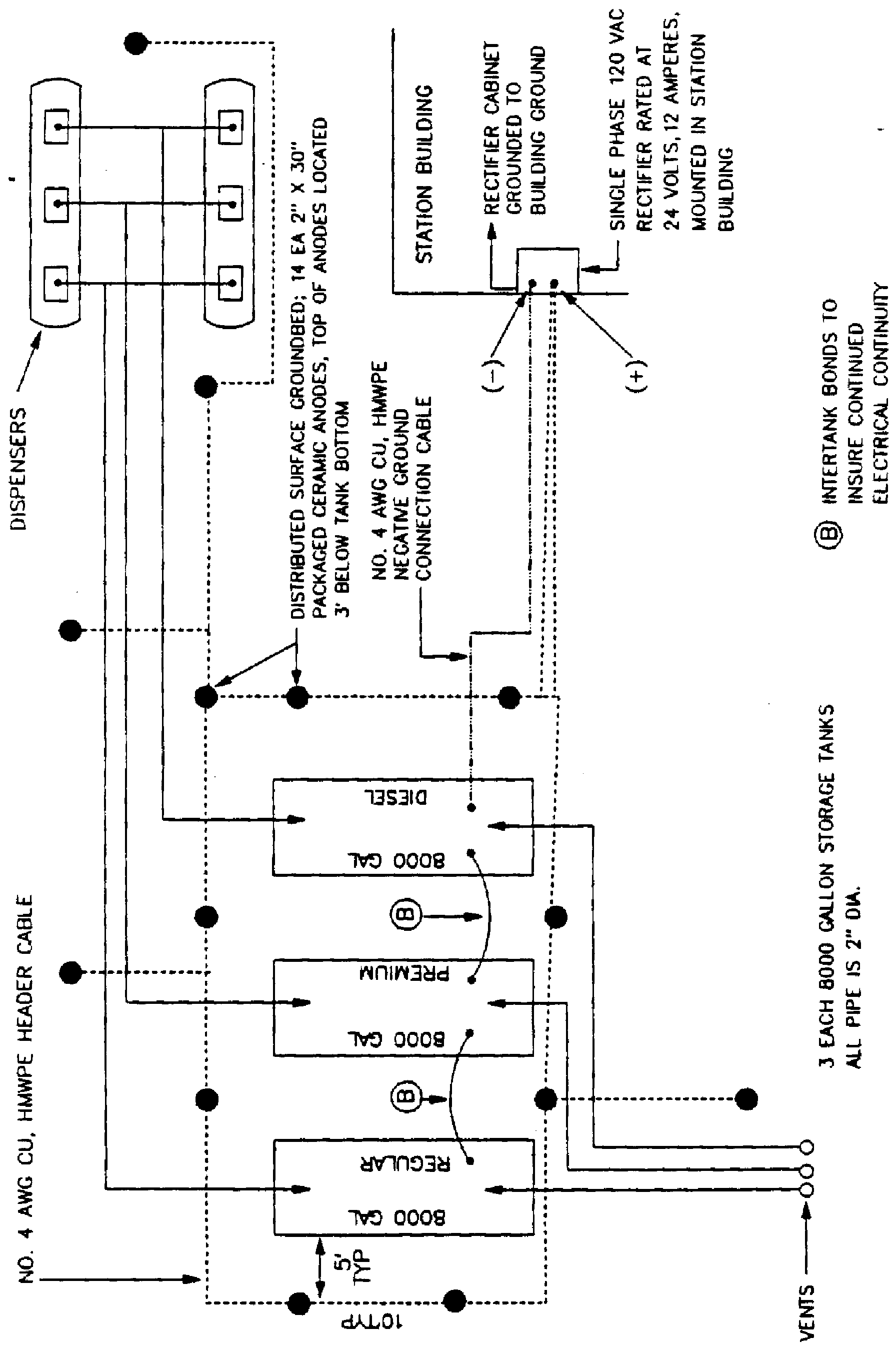


Figure 2-5 Cathodic Protection for Underground Storage Tanks and Piping

Area of 3 tanks = 3 [2 x 3.14 x 4^2 +3.14 x 8 x 21.25]
= 1905 sq ft

Area per lin ft of 2-in. pipe = 0.621 sq ft/ft (from table A-2)

Total pipe area = 750 ft x 0.621 sq ft/ft = 466 sq ft

Total area = 1905 sq ft + 466 sq ft = 2371 sq ft

2) Check the current requirement (I) using equation 1-1:

$$I = (A)(I')(1.0-C_E)$$

Where:

A = 2371 sq ft (External tank and piping surface area from previous calculation)

I' = 2 mA/sq ft (Required current density [assumed])

C_E = 0.00 (Coating efficiency expressed in decimal form from item 2 of paragraph 2-3a)

I = 2371 sq ft (2 mA/sq ft) x (1.0 - 0.0)

I = 4742 mA or 4.7 amp.

The 4.7 amp would be reasonable for the facility if it were insulated. The actual current requirement of 8.2 amp occurs because of current loss to other underground structures and is also reasonable in relation to that calculated for an isolated facility.

3) Select an anode and calculate the number of anodes required (N) to meet the design life requirements.

Calculations can be run on several size anodes, but in this case 2-in. by 60-in. packaged rod anodes (rod size = 0.125 in x 4 ft long) are chosen for ease of construction. Using equation 1-2, the number of anodes required to meet the cathodic protection system design life can be calculated:

$$N = \frac{I}{I_A}$$

Where:

I = 8.2 amp (Current requirement from item 10 of paragraph 2-3a)

I_A = 1.0 amps/anode (Current rating per anode from table 3-3)

$N = \frac{8.2}{1.0}$ = 8.2 anodes; use nine, 2-in. by 60-in. packaged rod anodes

4) Calculate the resistance of a single anode-to-earth (R_A) from equation 1-6:

$$R_A = \frac{p\ K}{L}$$

Where:

P = 4500 ohm-cm (Soil resistivity from item 1 of paragraph 2-3a)

K = 0.0234 (Shape function from table A-4 [where: L/d = 60 in./2 in. = 30])

L = 5 ft (60 in.) (Effective anode length).

d = 2 in. (Anode/backfill diameter)

$$R_A = \frac{4500 \times 0.0234}{5}$$

R_A = 21.06 ohms

5) Calculate the number of anodes required to meet maximum anode groundbed resistance requirement. A distributed anode array does not lend itself to an exact calculation of equation 1-11 because the anodes are positioned at various locations and are not located in a straight line. Equation 1-11 assumes a straight line configuration. However, to approximate the total anode-to-earth resistance, equation 1-li may be used.

$$R_N = \frac{R_A}{N} + \frac{p\ P_F}{C_c}$$

Where:

R_N = Groundbed-to-earth resistance

R_A = 21.06 ohms (Resistance of a single anode-to-earth from the previous calculation)

p = 4500 ohm-cm (Soil resistivity from item 1 of paragraph 2-3a)

C_C = 10 ft (Estimated approximate spacing of anodes)

P_F = 0.00212 (Paralleling factor from table 3-5; assume 9 anodes; reasoning is the same as in step 5, paragraph 2-2b)

N = 9 anodes (Estimated number of anodes required; from step 3, paragraph 2-2b)

$$R_N = \frac{21.06}{9} + \frac{4500 \times 0.00212}{10}$$

R_N = 3.29 ohms.

Resistance is too high. Additional calculations using an increasing number of anodes (i.e., 11, 12, 13, 14, etc.) have to be made; these calculations show that fourteen anodes will yield a groundbed-to-earth resistance of 2.26 ohms.

6) Select the number of anodes to be used. The numbers determined are:

For life = nine anodes maximum required
For resistance = fourteen anodes maximum required

Therefore, the larger number of anodes, fourteen, is selected.

7) Determine the total circuit resistance (RT) from equation 1-3:

$$R_T = R_N + R_W + R_C$$

Where:
R_N = Groundbed resistance (ohms)
R_W = Header cable/wire resistance (ohms)
R_C = Structure-to-earth resistance (ohms).

a) Groundbed resistance (RN) from step 5.

R_N = 2.26 ohms

b) Header cable/wire resistance (R_W) from equation 1-15:

$$R_W = \frac{L_W \, R_{MFT}}{1000 \text{ ft}}$$

Where:
L_W = 150 ft (Effective cable length. The loop circuit makes calculating effective wire resistance complex. Since current is discharged from anodes spaced all along the cable, one-half the total cable length may be used to approximate the cable resistance. Total cable length = 300 ft. Effective cable length = ½ (300 ft) = 150 ft.)

R_{MFT} = 0.254 ohm (This is the resistance per 1000 lin ft of No. 4 AWG cable, which has been selected for ease of handling.)

$$R_W = \frac{150 \text{ ft} \times 0.254 \text{ ohm}}{1000 \text{ ft}}$$

R_W = 0.038 ohm; use 0.04 ohm

c) Structure-to-earth resistance.

Since the tanks and piping are essentially bare and are not electrically isolated, structure-to-earth resistance may be considered negligible. Therefore R_C = 0.

d) Calculate total circuit resistance (RT) from equation 1-3:

$$R_T = R_N + R_W + R_C$$

$$R_T = 2.26 + 0.04 + 0 = 2.30 \text{ ohms}$$

Since the design requirements call for a maximum groundbed resistance of 2.5 ohms and RT = 2.30 ohms, the design using fourteen 2-in. by 60-in. packaged ceramic anodes will work.

8) Calculate the rectifier voltage (V_{REC}) from equation 1-17:

$$V_{REC} = (I)\ (R_T)\ (120\%)$$

Where:

I = 8.2 amp (Current requirement from step 2, paragraph 2-3b)

R_T = 2.30 ohms (Total circuit resistance from previous calculation)

120% = Rectifier voltage capacity design safety factor.

V_{REC} = 8.2 amp x 2.30 ohms x 1.2

V_{REC} = 22.6 V

c. Select rectifier.

Based on the design requirement of 22.6 V and 8.2 amp, a rectifier can be chosen. A 12-amp, 24-V unit is selected because this is the nearest standard commercial size available.

2-4. On-Grade Tank Bottoms.

Four on-grade fuel oil storage tanks are to be constructed with the configuration shown on figure 2-6. This design may be prohibited if secondary containment uses a nonconductive membrane beneath the tanks. The membrane would not allow the cathodic protection current to flow from the remotely located deep anode through the nonconductive membrane to the tank bottoms. If this situation exists, a distributed anode design with the anodes located between the membrane and the tank bottoms would have to be used. All piping will be above grade. To minimize the extent of underground cable, it was decided to use a deep anode groundbed, located just outside the spill containment dikes. (Note: Some county, state, or federal agencies such as the EPA may have regulations that affect the use of deep anode beds because they can provide a conduit for the mixing of water between aquifer levels. In such cases, regulations have sometimes required cementing of the annulus between the deep anode bed casing and the augered hole to prevent this water migration. The system designer should check with the applicable agencies before committing to a deep anode design. Figures 2-7, 2-7A, 2-8, and 2-8A illustrate a typical deep anode groundbed using ceramic rod anodes. The tank bottoms will be bare. All piping will be above ground. The tanks will be dielectrically insulated from the structures. Field tests were made at the site and the subsurface geology was determined to be suitable for a deep anode groundbed (reference 25).

a. Design data.

1) Soil resistivity at anode depth is 1500 ohm-cm.

2) Tanks are 75 ft in diameter.

3) Design cathodic protection anodes for a 15-year life.

4) Design current density is 2 A per sq ft of tank bottom.

5) Since the tanks are electrically isolated from each other, intertank bonds will be required.

6) The cathodic protection system circuit resistance should not exceed 0.75 ohm.

7) Electric power is available at a switch rack in an unclassified (nonexplosion proof) area 125 ft from the desired groundbed location, 230 V AC, single phase.

8) Since the exterior bottom of these type tanks are always bare, the coating efficiency will equal 0.00.

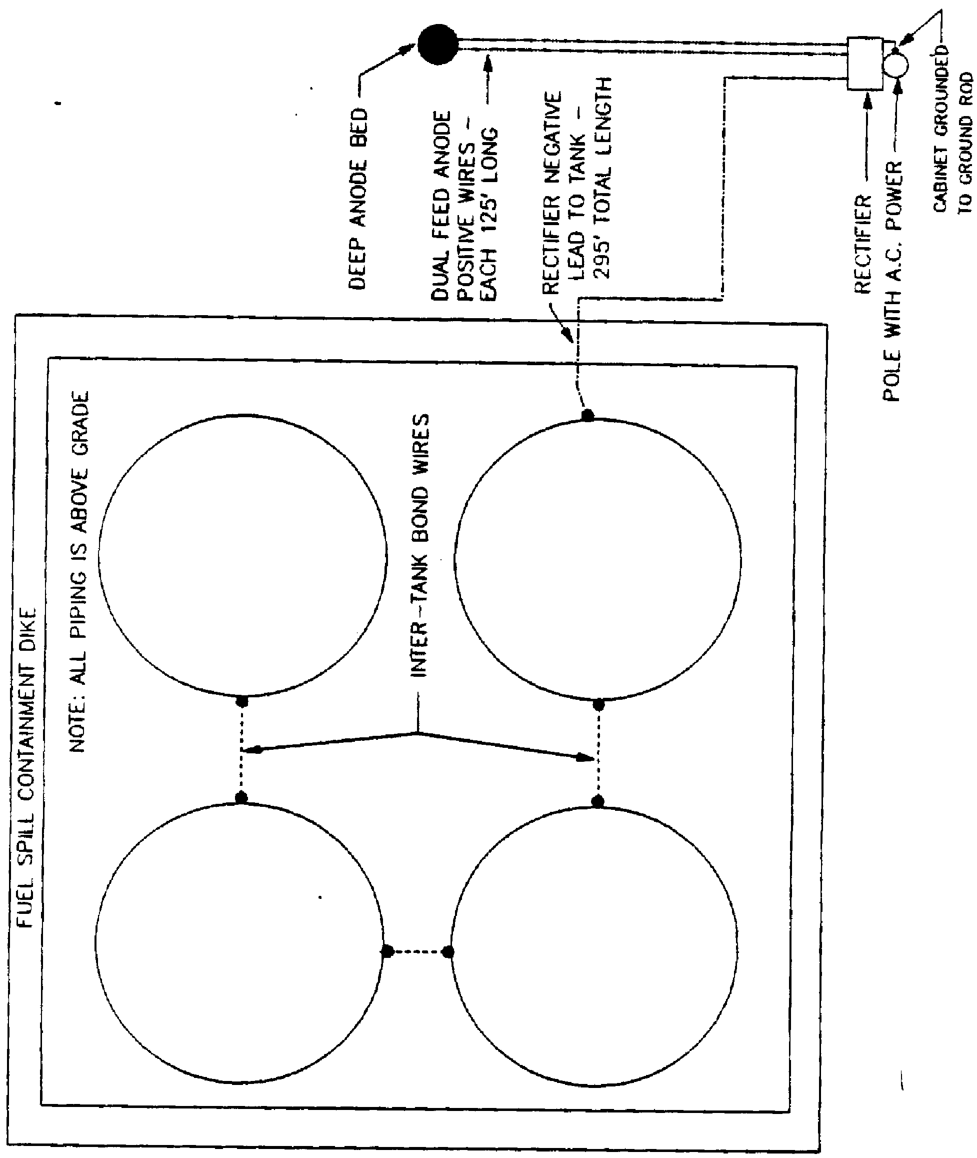


Figure 2-6 On-Grade Tank Bottoms

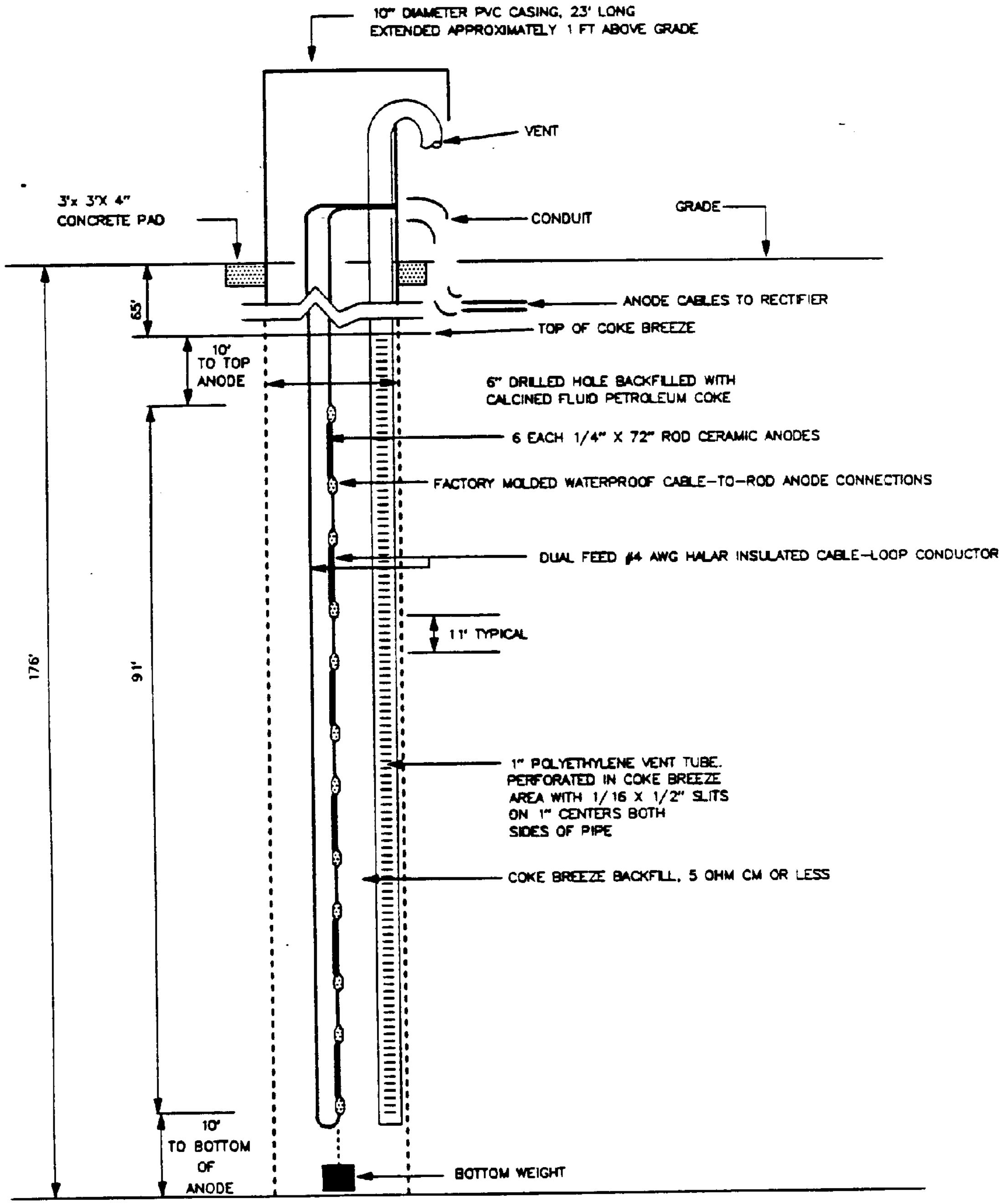


Figure 2-7 Typical Deep Anode Groundbed Using Rod Angles

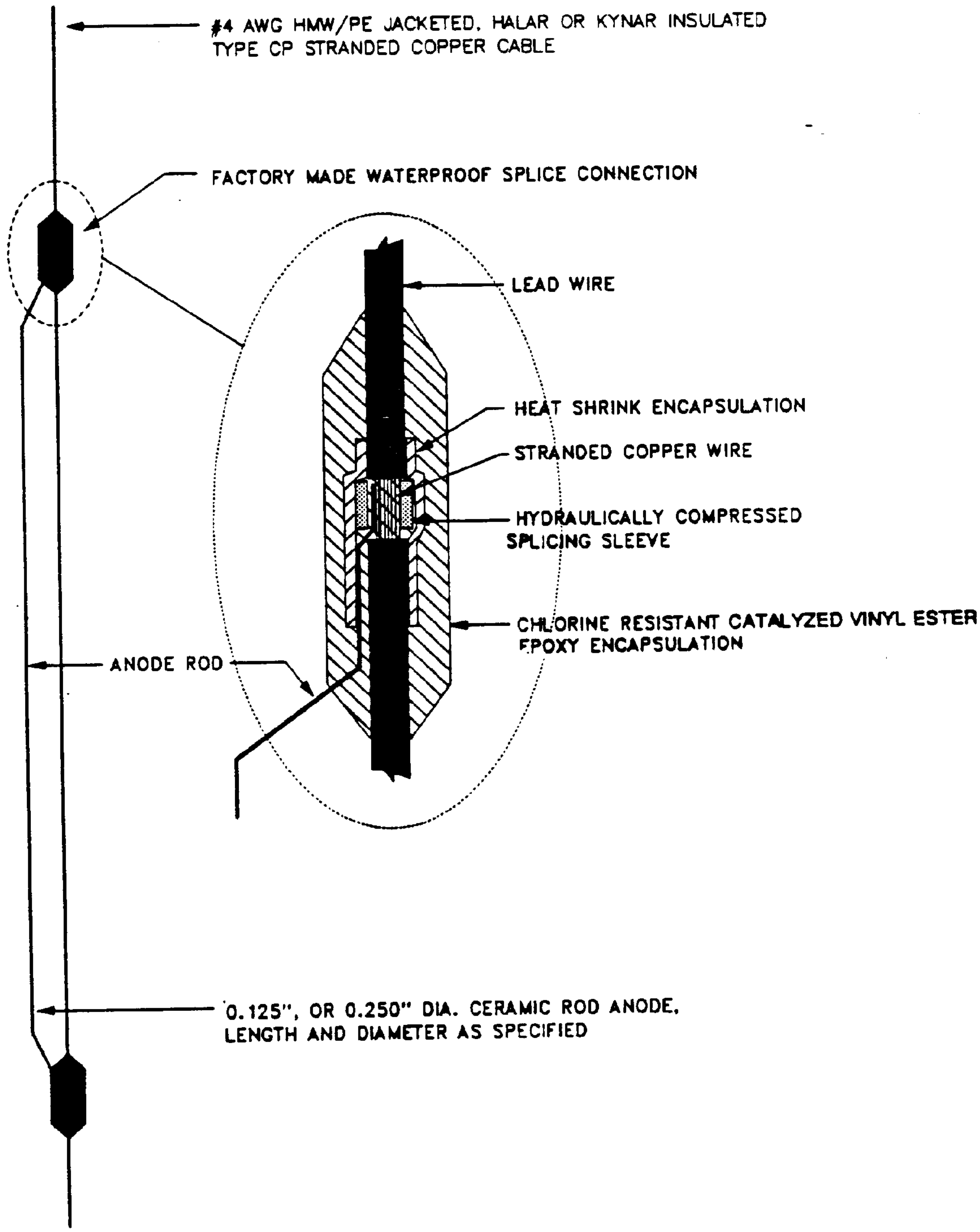


Figure 2-7A Ceramic Rod Anode for Deep Groundbed Use

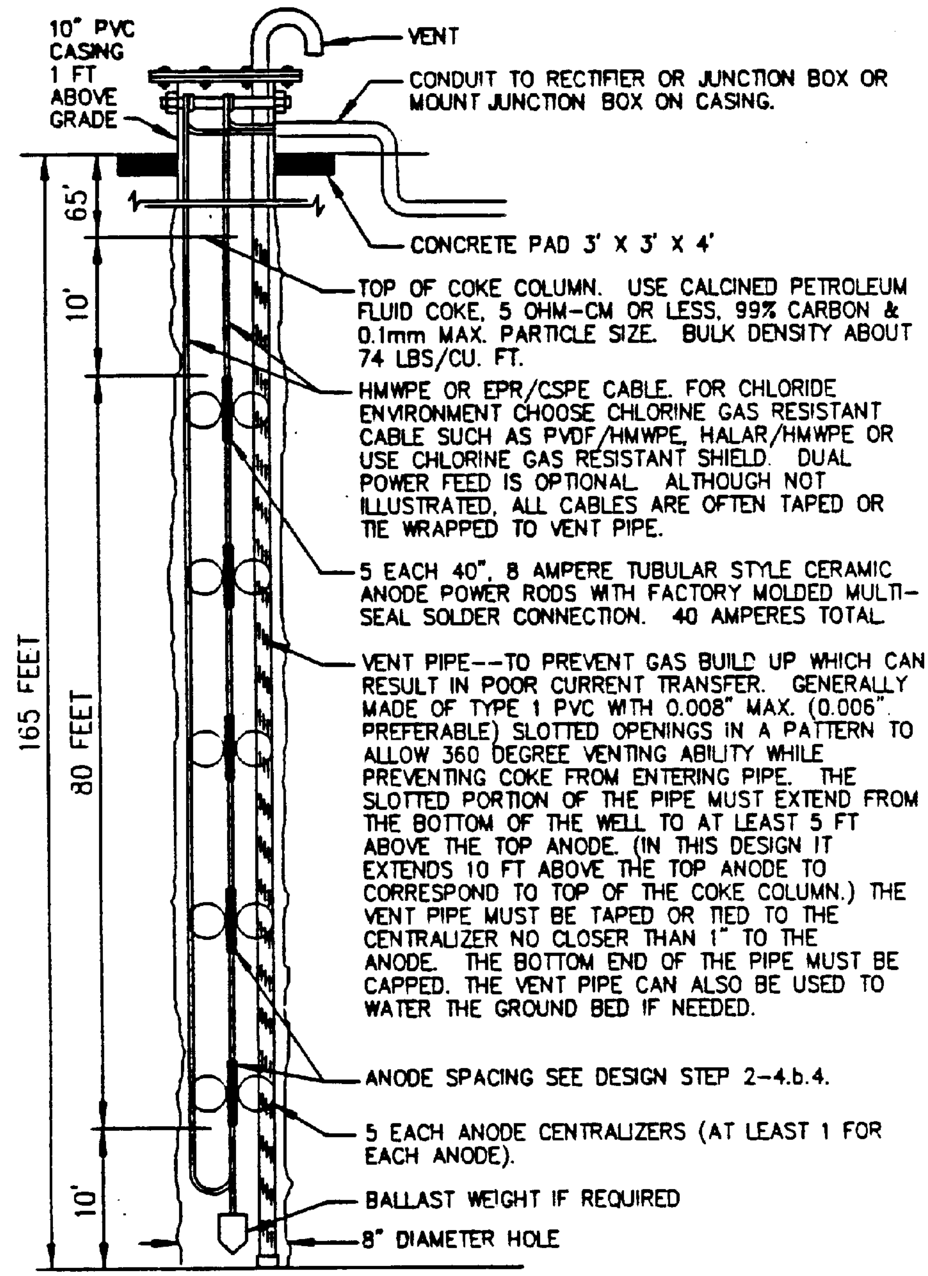


Figure 2-8 Ceramic Anode Tubular Power Rod Used in Deep Anode Bed.

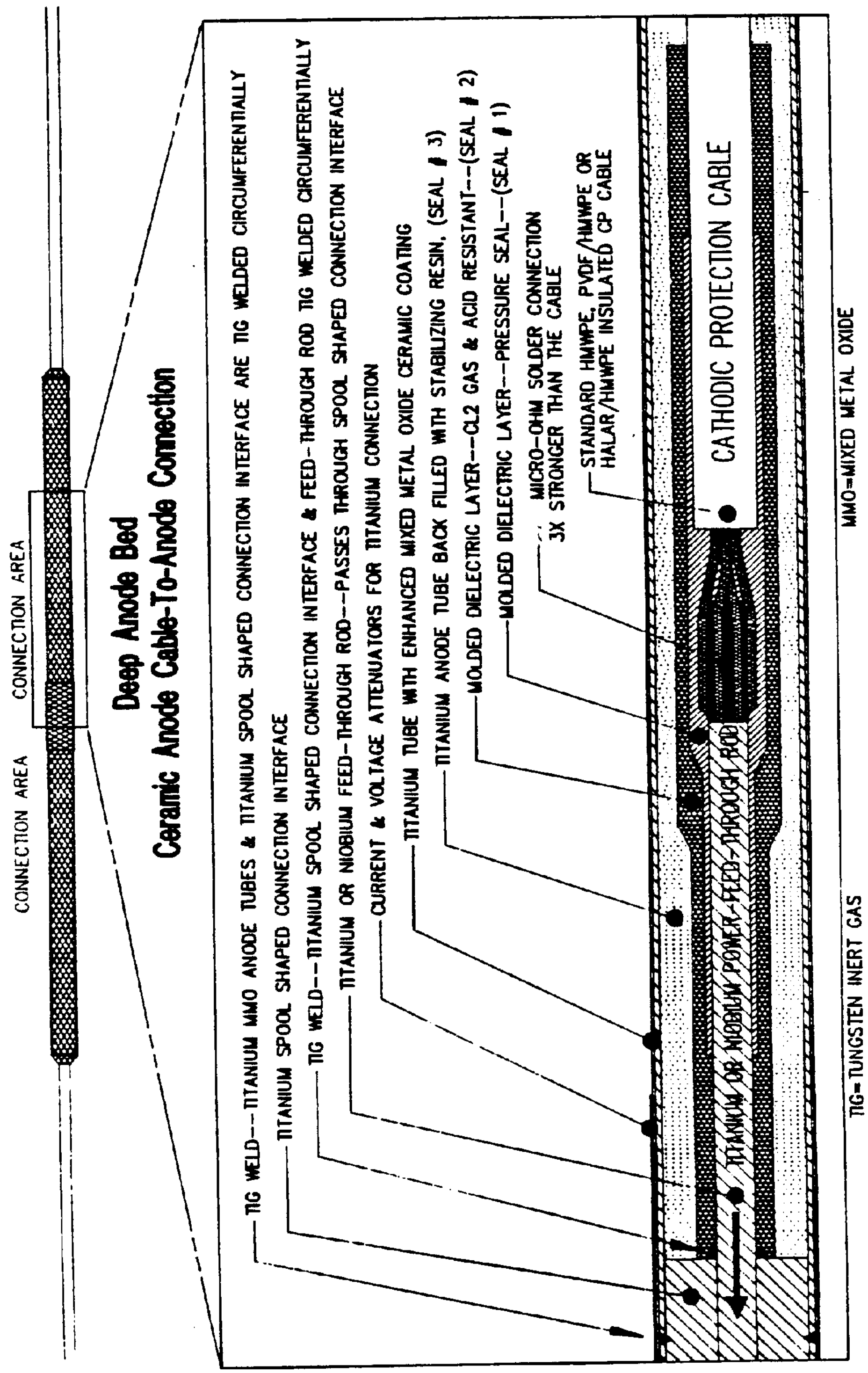


Figure 2-8A. Ductile Ceramic Anode Tubular Power Rod

b. Computations.

1) Find the surface area to be protected.

Area of each tank bottom = B r^2:
A = B x 37.5^2 = 4418 sq ft

Area of the four bottoms:
A = 4 x 4418 = 17,672 sq ft

2) Determine the current requirement (I) from equation 1-1:

$$I = (A)\ (I')(1.0 - C_E)$$

Where:

A = 17,672 sq ft (Total surface area from previous calculation)

I' = 2 mA/sq ft (Current density from item 4 of paragraph 2-4a)

C_E = 0.0 (bare) (Coating efficiency from item 8 of paragraph 2-4a)

I = 17,672 sq ft x 2 mA/sq ft x (1.0 - 0.0)

I = 35 amp

3) Select an anode and calculate the number of anodes (N) required to meet the design life. The deep anode groundbed will consist of a series of rods connected to a continuous header cable. For physical strength, the 1/8-in. or 1/4-in. diameter rods are usually chosen. To ensure good transmission of current in to the backfill column, long anodes, typically 6 ft or 8 ft are used. For this example, 1/4-in. diameter by 72-in. long rods have been chosen. Using equation 1-2:

$$N = \frac{I}{I_A}$$

Where:

I = 35 amp (Current requirement from previous calculation)

I_A = 6.6 amp/anode (Current rating per heavy duty coated anode from table 3-3)

$$N = \frac{35}{6.6} = 5.3\text{; use 6 anodes}$$

4) Calculate the required length of the backfill column.

Spacing between anodes depends primarily on the resistivity of both the backfill column (coke breeze). If low resistivity calcined fluid petroleum coke is used, than the spacing between rod anode (1/8-in. and 1/4-in. diameter) should not be greater than twice the individual rod length. Based on previous design experience, a spacing between anode rods of 11 ft is selected.

The minimum length of the backfill column is then calculated as follows:

6 anodes at 6 ft per anode =	36 ft
Spacing between anodes: 5 at 11 ft =	55 ft
Space above and below anode string* =	20 ft
Total length	111 ft

* Generally, the coke breeze column extends from 10 ft below the bottom anode to 10 ft above the top anode as shown in figures 2-7 and 2-8.

5) Calculate the backfill column-to-earth resistance (R_A).

This can be done from equation 1-4. Because several attempts may have to be made to obtain the required groundbed resistance, the process is facilitated by using the curves in figures 2-9A through 2-9C. Typical hole diameters are 6 or 8 in.; a 6-in. diameter hole has been selected for this groundbed. Figure 2-9C will be used for this design.

Figure 2-9C shows that, for a 111-ft long coke breeze backfill column, the resistance to earth per 1000 ohm-cm is 0.31 ohm. In 1500 ohm-cm soil, the resistance is 0.31 x 1500/1000 = 0.47 ohm (groundbed resistance in 1000 ohm-cm soil, times actual soil resistivity in ohm-cm per 1000). This is well below the design requirement of 0.75 ohm.

6) Determine total circuit resistance (RT) from equation 1-3 :

$R_T =$ $R_A + R_W + R_C$ (Because the cathodic protection system utilizes a single deep anode groundbed $R_A = R_N$)

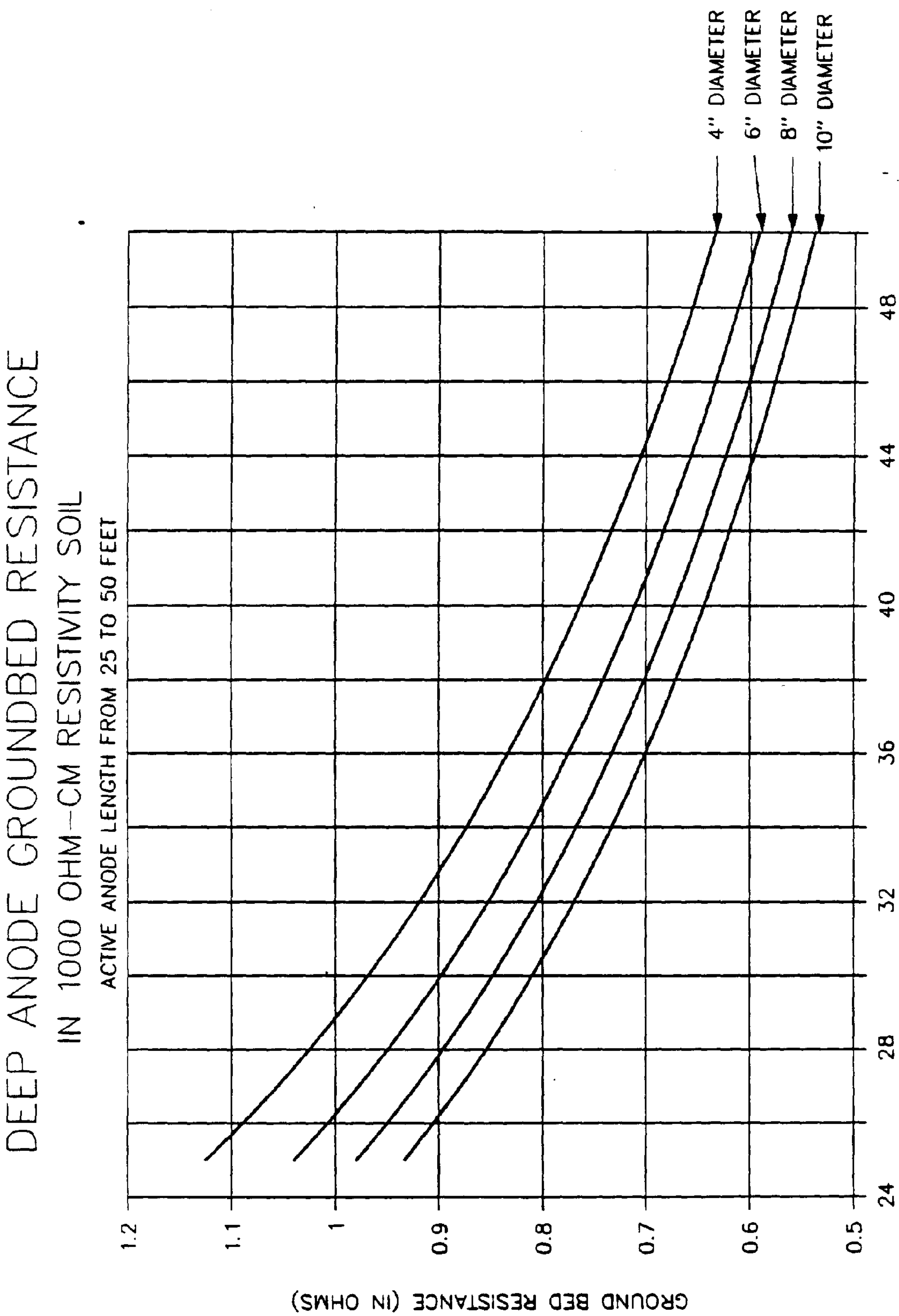


Figure 2-9A Deep Anode Groundbed Resistance 25 to 50 ft.

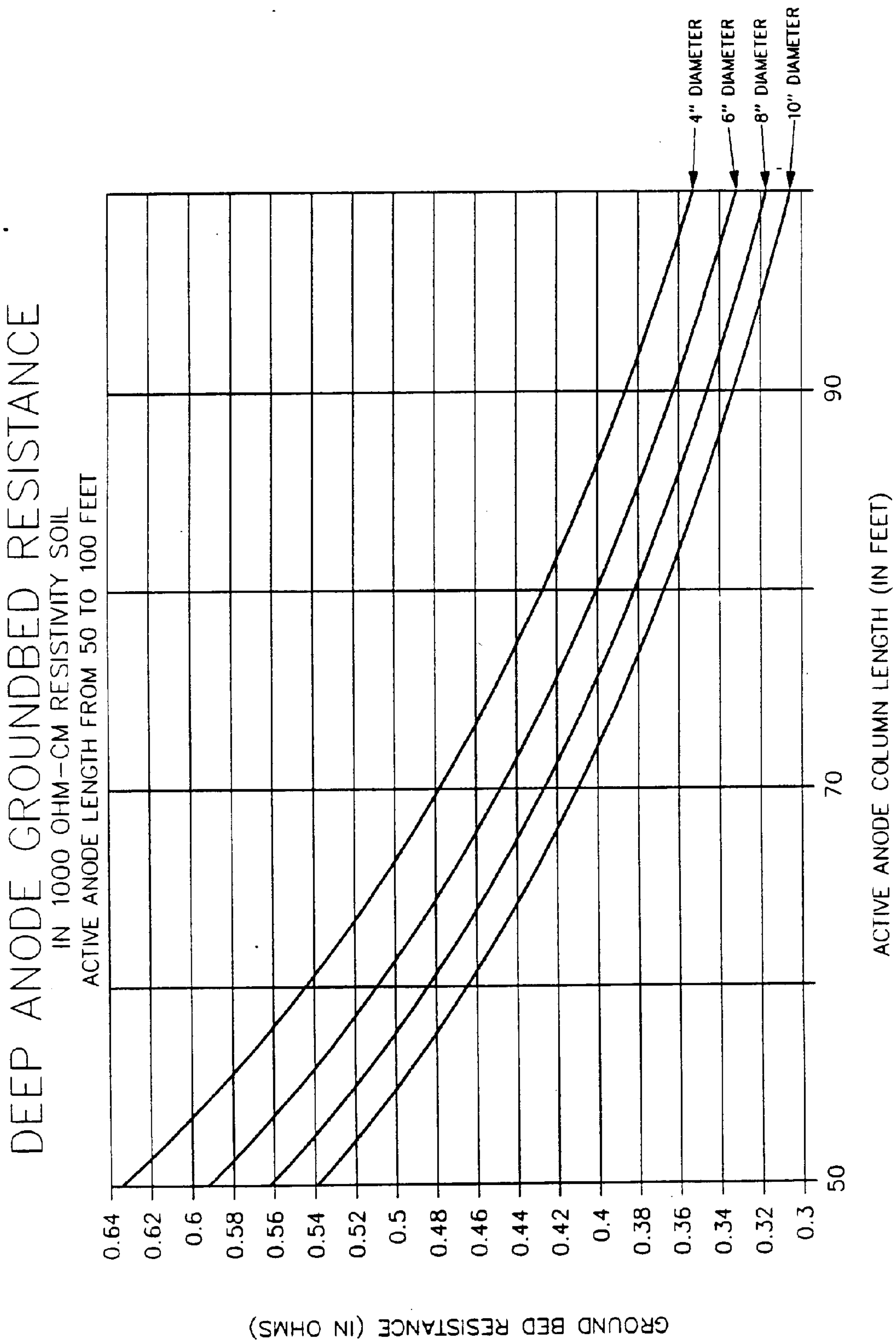


Figure 2-9B Deep Anode Groundbed Resistance 50 to 100 ft.

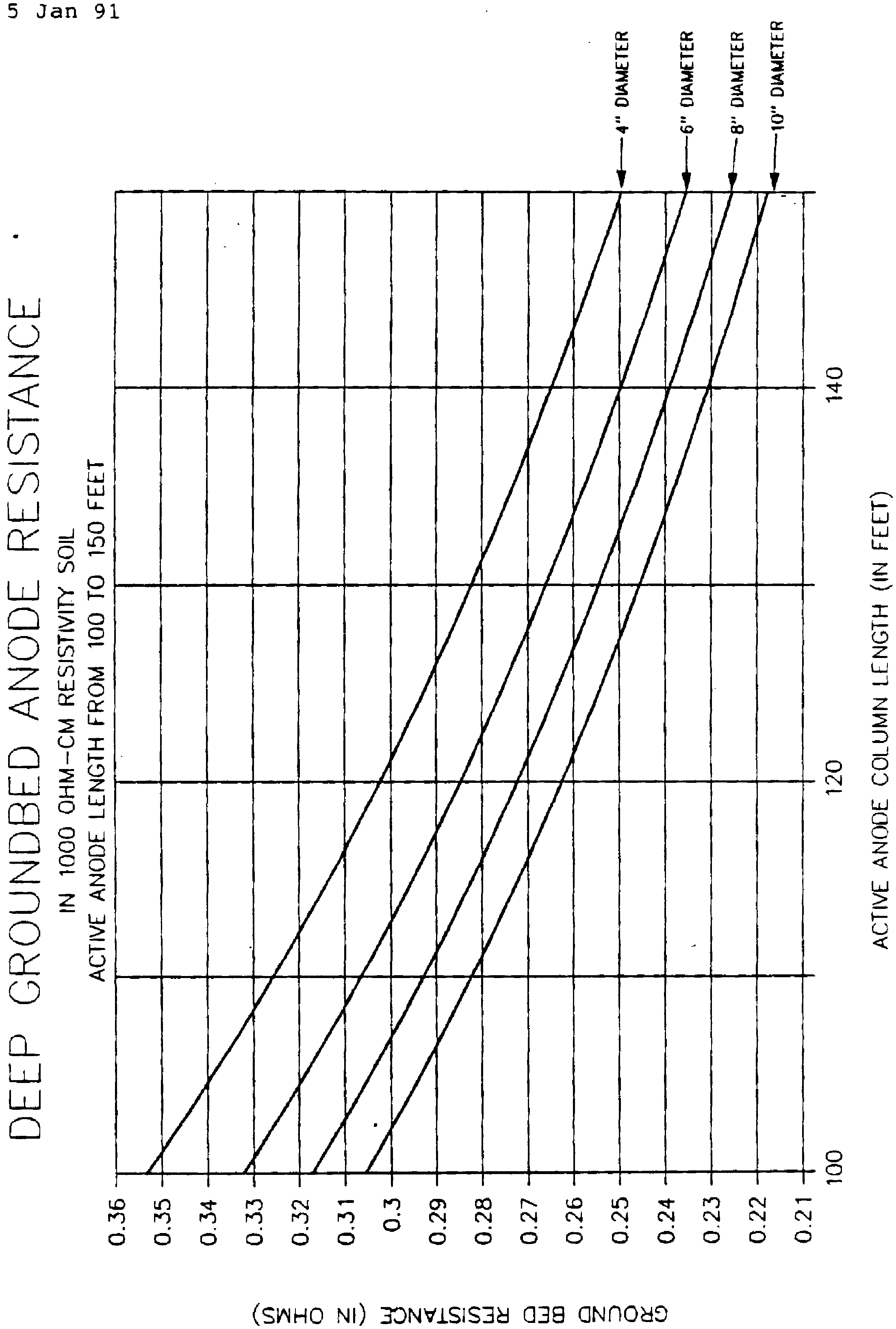


Figure 2-9C Deep Anode Groundbed Resistance 100 to 150 ft.

Where:

R_A = Backfill column-to-earth resistance (ohms), calculated in step 5 above

R_W = Header cable/wire resistance (ohms)

R_C = Structure-to-earth resistance (ohms).

a) Backfill column-to-earth resistance (RA) from step 5:

$$R_A = 0.47 \text{ ohm}$$

b) Wire resistance

A deep anode groundbed is defined as one where the top of the backfill column is at least 50 ft below the surface of the earth. Actual depth will vary, depending on subsurface geology and the distance over which the current is expected to spread. In this example, 65 ft was selected as the depth to the top of the coke breeze column. The anodes can be supplied through a single or dual feed. Dual feed is preferred to reduce both the resistance of the circuit and the chance of a failure due to a cable break.

No. 4 AWG cable has been chosen. Cable lengths have been calculated based on the following distances, illustrated in the deep groundbed example shown in figure 2-7.

From grade to top of backfill column	65 ft
From top of backfill column to top anode	10 ft
From grade to bottom of backfill column	176 ft
From bottom anode to bottom of backfill column	10 ft
From anode hole to rectifier 2 cables at 125 ft	250 ft
From top of anode assembly to bottom of anode assembly	91 ft
Total cable length from top anode feed to rectifier 125 ft + 65 ft + 10 ft=	200 ft
Total cable length from bottom anode feed to rectifier 125 ft + 176 ft - 10 ft =	291 ft

Calculate top cable resistance (R_{WT}) from equation 1-15:

$$R_{WT} = \frac{L_{WT}\ R_{MFT}}{1000\ \text{ft}}$$

Where:

L_{WT} = 200 ft (Cable length from previous calculation)

R_{MFT} = 0.254 ohm (Resistance per 1000 lin ft of No. 4 AWG cable which has been selected for installation. These resistance values can be found in table 3-6).

$$R_{WT} = \frac{200\ \text{ft} \times 0.254\ \text{ohm}}{1000\ \text{ft}} = 0.051\ \text{ohm}$$

Calculate bottom cable resistance (R_{WB}) from equation 1-15:

Where:

L_{WB} = 291 ft (Cable length from previous calculation)

R_{MFT} = 0.254 ohm (Cable resistance per 1000 lin ft [same as above])

$$R_{WB} = \frac{291 \text{ ft} \times 0.254 \text{ ohm}}{1000 \text{ ft}} = 0.074 \text{ ohm}$$

These two cables are in parallel, so that their wire resistance ($R_{T/B}$) is calculated from the law of parallel circuits:

$$\frac{1}{R_{T/B}} = \frac{1}{R_{WT}} + \frac{1}{R_{WB}}$$

$$\frac{1}{R_{T/B}} = \frac{1}{0.051} + \frac{1}{0.074}$$

$$\frac{1}{R_{T/B}} = 19.6 + 13.5 = 33.1$$

$$R_{T/B} = 0.030 \text{ ohm}$$

Since current is dissipating along the portion of the cable to which the anodes are connected, the resistance of this cable (R_{POS}) is taken as one half its total resistance as was done in example 2-2.

$$R_{POS} = \frac{L_W\ R_{MFT}}{1000 \text{ ft}} \times \frac{1}{2} = \frac{91 \text{ ft}* \times 0.254 \text{ ohm/ft}}{1000 \text{ ft}} \times \frac{1}{2}$$

*91 ft is the overall anode column length including the interconnecting wire from the top of the top anode to the bottom of the bottom anode (see item 4 from paragraph 2-4b.)

$$R_{POS} = 0.012 \text{ ohm}$$

Negative circuit wire resistance must also be calculated:

Negative cable from rectifier to closest tank = 125 ft of No. 4 AWG

Intertank bonds = 170 ft of No. 4 AWG**

**The two intertank bond circuits are in parallel and of about the same length. From the law of parallel circuits, total resistance of two parallel circuits of equal resistance is one half the resistance of each circuit.

Therefore, one half the cable length is used in this calculation. The calculation is also conservative since not all the current flows through the complete intertank bond circuit.

Total ft of negative circuit wire = 295 ft of No. 4 AWG cable

Negative resistance if calculated from equation 1-15:

$$R_{NEG} = \frac{L_W \, R_{MFT}}{1000 \text{ ft}}$$

Where:

L_W = 295 ft (Negative cable length)

R_{MFT} = 0.254 ohm (Negative cable resistance per 1000 un ft of No. 4 AWG cable [table A-6])

$$R_{NEG} = \frac{295 \times 0.254}{1000}$$

R_{NEG} = 0.074

Total wire resistance therefore is:

$R_W = R_{T/B} + R_{POS} + R_{NEG} = 0.030 + 0.012 + 0.074$

R_W = 0.116 ohm

Cable insulation is also important. High molecular weight polyethylene insulation, commonly used for cathodic protection work, tends to blister, become brittle, and then crack in deep groundbed use where chlorine gas generation can occur. This has been most prevalent in open holes containing brackish water, but may occur in coke breeze backfilled holes also. Consequently, to minimize the chances of cable failure, one of the two following types of insulation, which show good resistance to these oxidizing environments should be used:

Polyvinylidene fluoride (Kynar)[1]

[1] Registered trademark of Penwalt Corp.

Copolymer of chlor-tri-fluorethylene and ethylene (Halar)[2]

To protect the insulation itself and to facilitate handling, cables for deep anode groundbeds also have an outer jacket of high-molecular weight polyethylene extruded over the Kynar or Halar insulation.

c) Structure-to-earth resistance (R_c).

Since the tank bottoms are bare, their resistance-to-earth is considered negligible, therefore, R_C is taken as zero.

d) Calculate total circuit resistance (RT) from equation 1-3:

$R_T = R_N + R_W + R_C$

$R_T = 0.470 + 0.116 + 0.0$

$R_T = 0.586$ ohm

This is well below the design requirement and, therefore, this groundbed with 6 - 1/4 in. by 6 ft ceramic anode rods with total backfill column length of 111 ft will be used.

7) Calculate rectifier voltage (V_{REC}) from equation 1-17:

$$V_{REC} = (I)\ (R_T)\ (120\%)$$

Where:

I = 35 amp (Current requirement from step 2, paragraph 2-4b)

R_T = 0.586 ohm (Total circuit resistance from previous calculation)

120% = Rectifier capacity safety factor

V_{REC} = 35 amp x 0.586 ohm x 120%

V_{REC} = 24.6 V

c. Select rectifier.

[2] Registered trademark of Allied Chemical Corp.

Based on the design requirement of 24.6 V and 35 amp, a rectifier can be chosen. A 30 V, 42 ampere unit is commercially available and is selected. This rectifier can be pole mounted as illustrated in figure 2-10.

d. Installation.

Figures 2-7 and 2-8 show this deep anode design.

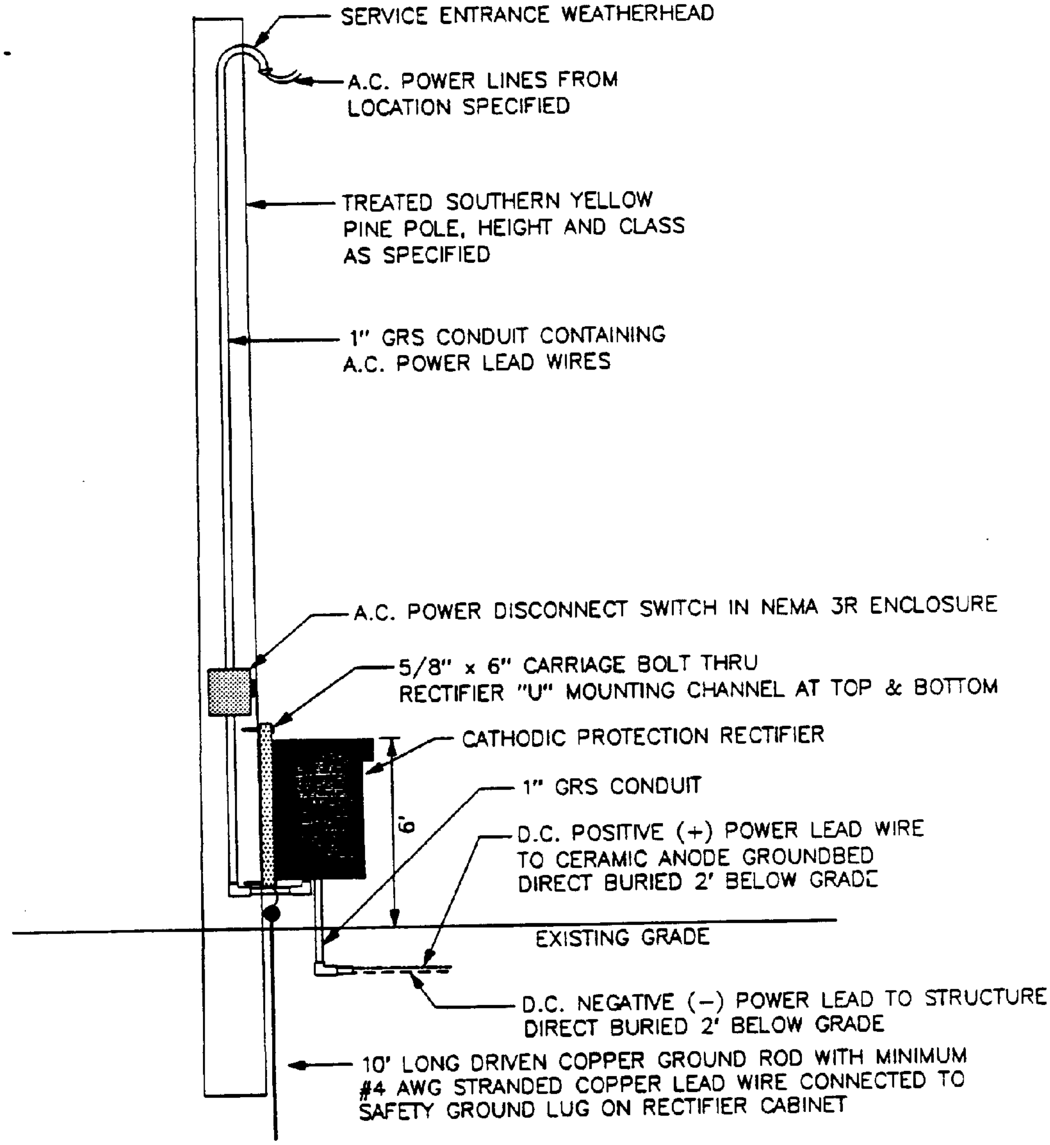


Figure 2-10 Pole-Mounted Rectifier

2-5. Gas Distribution System.

It has been decided to install cathodic protection on the gas distribution piping in a post housing facility. Figure 2-11 shows a portion of the piping.

The water distribution system has recently been replaced with nonmetallic pipe. On this basis, it has been decided that the gas piping can be protected with impressed current from a deep anode groundbed without causing interference to the water pipe. (Note: Some county, state, and federal agencies such as the EPA may have regulations which prevent the use of deep anode beds because they can provide a conduit for mixing of waters between aquifer layers. In such cases, regulations have required cementing of the annulus between the deep anode bed casing and the augered hole to prevent this water migration. The system designer should check with the applicable agencies before committing to a deep anode design.)

a. Design data.

1) Experience in the area shows the subsurface resistivity at a depth of 50 and 200 ft to be 2000 ohm-cm.

2) Piping consists of:

   28,000 ft of 1 1/4-in. diameter pipe
   1,200 ft of 4-in. diameter pipe
   3,600 ft of 6-in. diameter pipe

3) Design cathodic protection anode for a 20-year life.

4) Experience with similar pipe in the same general soil type has shown that a design current density of 2 A per sq ft of bare pipe is conservative.

5) Piping is welded steel, poorly coated; considered to be bare for protection purposes and, therefore, the coating efficiency is 0.0 (CE = 0.0).

6) Piping is isolated at each house and at the tie-in to the main supply line.

7) The cathodic protection circuit resistance should not exceed 1 ohm.

8) 120/240 V AC, single phase power is available.

9) Current requirement tests are not practiced in this case, so design will be based on calculations. (Note: Current requirement tests should be conducted whenever practicable.)

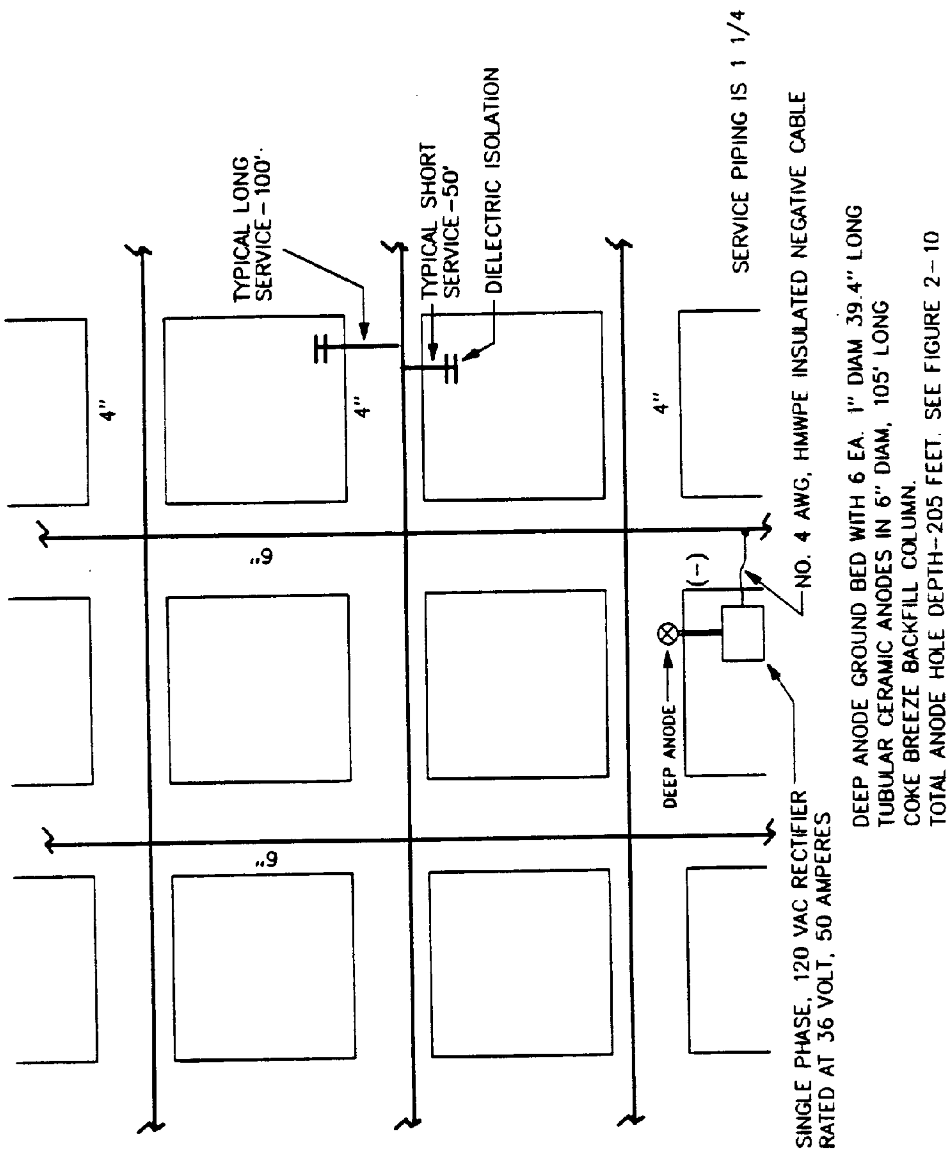


Figure 2-11 Deep Anode Cathodic Protection for Gas Distribution System

b. Computations.

1) Calculate the external surface area of the pipe (A) to be protected.

Pipe diameter	Length	Unit Area* (sq ft/lin ft)	Area (sq ft)
1 1/4 in.	28,000 ft	0.434	12,152
4 in.	1,200 ft	1.178	1,414
6 in.	3,600 ft	1.734	6,242
*from table A-2		Total	19,808

2) Determine current requirement (I) from equation 1-1:

$$I = (A)(I')(1.0 - C_E)$$

Where:

A = 19,808 sq ft (Surface area of pipe to be protected from previous calculation)

I' = 2 mA/sq ft (Current density, from item 4, paragraph 2-5a)

C_E = 0.0 (Coating efficiency [bare pipe])

I = 19,808 sq ft x 2 mA/sq ft x (1.0 - 0.0)

I = 39,616 mA or 39.6 amp; use 40 amp

3) Select an anode and calculate the number of anodes required (N) to meet the design life. For this design, tubular anodes have been chosen. The groundbed will consist of a series of anodes attached to a continuous header cable. A typical size tubular ceramic anode used in deep anode beds, 1-in. diameter by 39.4 in. long, is selected. The number of anodes are determined using equation 1-2:

$$N = \frac{I}{I_A}$$

Where:

I = 40 amp (Current requirement from previous calculation)

I_A = 8.0 amp/anode (Current rating per anode from table 3-3 [in coke breeze])

$$N = \frac{40}{8} = 5 \text{ anodes}$$

To allow a factor of safety, use 6 anodes

4) Calculate the required length of the backfill column.

The maximum allowable spacing between anodes depends primarily on the resistivity of the backfill column (coke breeze). For tubular anodes of ½-in. diameter or greater, maximum spacing between anodes should not exceed four times the anode tube length. For this example, we will try the maximum allowable spacing of 13 ft (39.4 in. x 4/12 = 13.1 ft).

The minimum length of the backfill column is calculated as:

6 anodes at 39.4 in. (3.3 ft) =	19.8 ft
Spacing between anode: 5 at 13 ft =	65.0 ft
Space above and below anode string*	20.0 ft
Total length	104.8 ft (use 105 ft)

* Generally, the coke breeze column extends from 10 ft below the bottom anode to 10 ft above the top anode.

5) Calculate the backfill column-to-earth resistance (R_A).

This can be done from equation 1-4. Because several attempts may have to be made to obtain the required resistance-to-earth, the process is facilitated by using the curve in figure 2-9C. Typical hole diameters are 6 or 8 in.; a 6-in. diameter hole has been selected for this groundbed.

From figure 2-9C for a 105 ft long coke breeze backfill column, the resistance to earth per 1000 ohm-cm is 0.325 ohm. In 2000 ohm-cm soil, the resistance is 0.325 x 2 = 0.65 ohm, which is below the design requirement defined in item 7 of paragraph 2-5a.

6) Determine total circuit resistance (R_T) from equation 1-3:

$R_T = R_A + R_W + R_C$ (Because the cathodic protection system uses a single deep anode groundbed $R_A = R_N$)

Where:

R_A = Backfill column-to-earth resistance (ohms).

R_W = Wire resistance (ohms).

R_C = Structure-to-earth resistance (ohms).

a) Backfill column-to-earth resistance (R_A) from step 5.

$$R_A = 0.65 \text{ ohm}$$

b) Wire resistance (R_W) from general equation 1-15:

$$R_W = \frac{L_W \, R_{MFT}}{1000 \text{ ft}}$$

A deep anode groundbed is defined as one where the top of the backfill column is at least 50 ft below the surface of the earth. Actual depth will vary, depending on subsurface geology and the distance over which the current is expected to spread. In this example, the depth to the top of the coke breeze backfill column was determined to be 100 ft. The anodes can be supplied through a single or dual feed. Dual feed is preferred to reduce both the resistance of the circuit and the chance of a failure due to a cable break.

The assembly is made on a single length of cable, beginning at the rectifier, running down through the tubular anodes to the bottom anode and then back up adjacent to the anodes to the rectifier. Resistance calculations are made as though there were three cables as noted below. The conductor provided with some tubular ceramic anodes is designated EPR/HY5O for one-in. diameter anodes and EPR/HY16 for 0.63-in. diameter anodes. These cables have an ethylene-propylene rubber inner insulation and a chlorosulphonated polyethylene outer jacket and are suitable for deep anode use if the insulation is protected with a chlorine-resistant sheath or shield.

EPR/HY50 cable has been chosen. The cable lengths have been calculated based on the following distances, which are illustrated in the deep groundbed examples shown in figures 2-12 and 2-13:

From grade to top of backfill column	100 ft
From top of backfill column to top anode	10 ft
From grade to bottom of backfill column	205 ft
From bottom anode to bottom of backfill column	10 ft
From anode hole to rectifier 2 cables at 10 ft	20 ft
From top of anode assembly to bottom of anode assembly	85 ft

Total cable length from top anode feed to rectifier 10 ft + 100 ft + 10 ft = 120 ft

Total cable length from bottom feed to rectifier 10 ft + 205 ft - 10 ft = 205 ft

Calculate top cable resistance (R_{WT}) from equation 1-15:

$$R_{WT} = \frac{L_{WT}\ R_{MFT}}{1000\ ft}$$

Where:

L_{WT} = 120 ft (Cable length from previous calculation)

R_{MFT} = 0.1183 ohm (Resistance per 1000 lin ft of EPR/HY5O [table 3-6])

R_{WT} = $\frac{120\ ft \times 0.1183\ ohm}{1000\ ft}$ = 0.014 ohm

Calculate bottom cable resistance (R_{WB}) from equation 1-15:

Where:

L_{WB} = 205 ft (Cable length from previous calculation)

R_{MFT} = 0.1183 ohm (Cable resistance per 1000 lin ft [same as above])

$$R_{WB} = \frac{205 \text{ ft} \times 0.1183 \text{ ohm}}{1000 \text{ ft}} = 0.024 \text{ ohm}$$

These two cables are in parallel, so that total resistance ($R_{T/B}$) is calculated from the law of parallel circuits:

$$\frac{1}{R_{T/B}} = \frac{1}{R_{WT}} + \frac{1}{R_{WB}}$$

$$\frac{1}{R_{T/B}} = \frac{1}{0.014} + \frac{1}{0.024}$$

$$\frac{1}{R_{T/B}} = 71.43 + 41.66 = 113.1$$

$$R_{T/B} = 0.009 \text{ ohm}$$

Since current dissipates along the portion of the cable to which the anodes are connected, the resistance of this cable (R_{POS}) is taken as one half its total resistance, as was done in example 2-2.

$$R_{POS} = \frac{L_W\ R_{MFT}}{1000 \text{ ft}} \times \frac{1}{2} = \frac{85 \times 0.1183 \text{ ohm/ft}}{1000 \text{ ft}} \times \frac{1}{2}$$

$$R_{POS} = 0.005 \text{ ohm}$$

Negative cable resistance: The rectifier is placed 25 ft from the connection to the piping, using No. 4 AWG HMWPE insulated cable. Negative resistance is calculated from equation 1-15:

$$R_{NEG} = \frac{L_W\ R_{MFT}}{1000 \text{ ft}}$$

Where:

L_W = 25 ft (Length of cable)

R_{MFT} = 0.254 ohm (Resistance per 1000 lin ft of No. 4 AWG HMWPE insulated cable [table A-6])

$$R_{NEG} = \frac{25 \times 0.254}{1000}$$

R_{NEG} = 0.006 ohm

Total wire resistance therefore is:

R_W = $R_{T/B}$ + R_{POS} + R_{NEG} = 0.009 + 0.005 + 0.006

R_W = 0.020 ohm

c) Structure-to-earth resistance (R_C).

The piping is essentially bare, so structure-to-earth resistance is negligible (R_C = 0.0).

d) Calculate total circuit resistance (R_C) from equation 1-3:

R_T = R_A + R_W + R_C (Because the cathodic protection system uses a single deep anode groundbed R_A = R_N)

R_T = 0.65 + 0.020 + 0.0

R_T = 0.670 ohm

7) Calculate rectifier voltage (V_{REC}) from equation 1-17:

V_{REC} = (I) (R_T) (120%)

Where:

I = 40 amp (Current requirement from step 2, paragraph 2-5b)

R_T = 0.670 ohm (Total circuit resistance from previous calculation)

120% = Rectifier voltage capacity design safety factor

$$V_{REC} = 40 \text{ amp} \times 0.670 \text{ ohm} \times 1.2$$

$$V_{REC} = 32.2 \text{ V}$$

c. Select rectifier.

Based on the design requirement of 32.2 V and 40 amp, a rectifier can be chosen. A 36-V, 50-amp unit is commercially available and is selected.

d. Installation.

Figures 2-12 and 2-13 show how the deep anode groundbed might look.

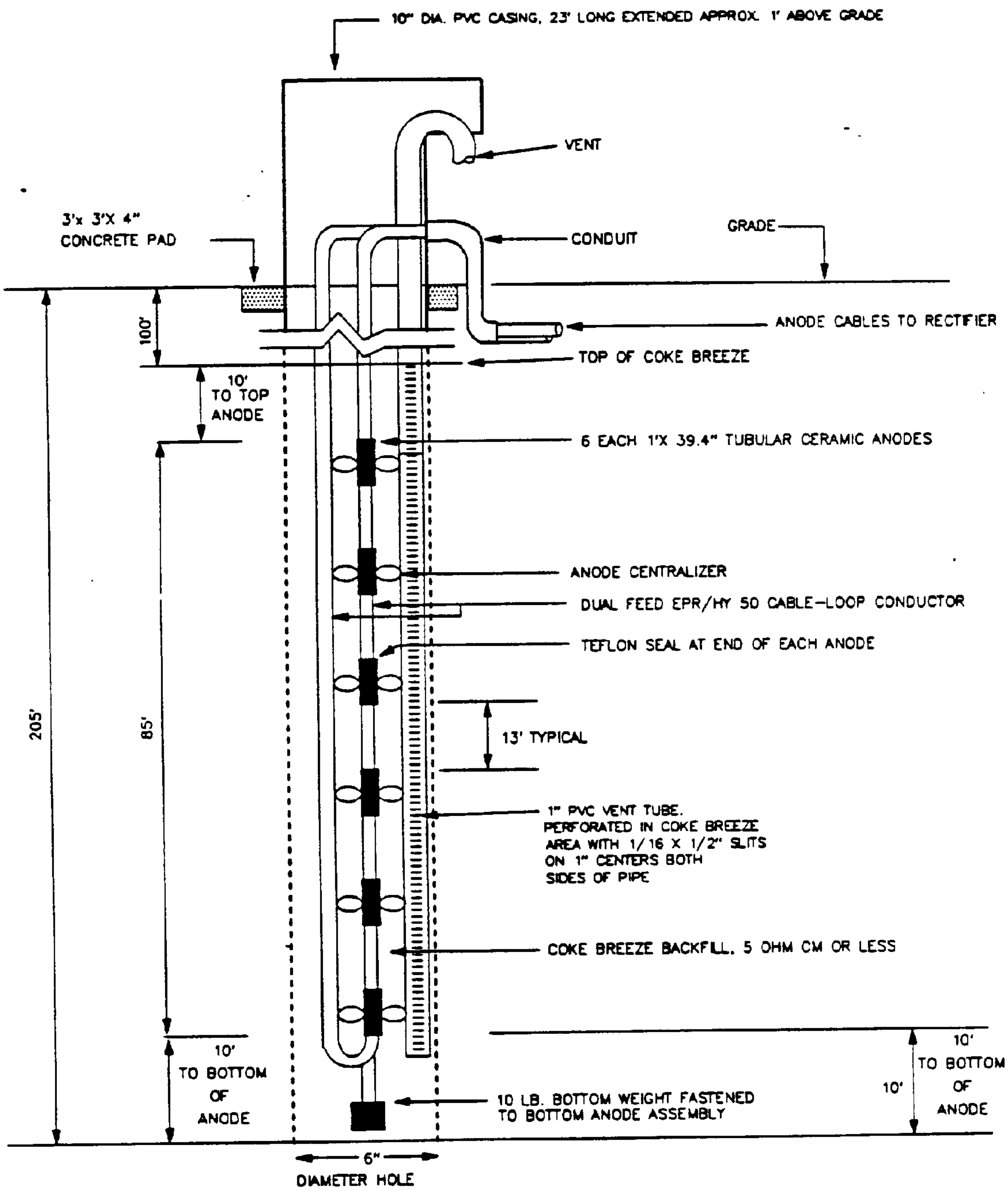


Figure 2-12 Typical Deep Anode Groundbed Using Tubular Anodes

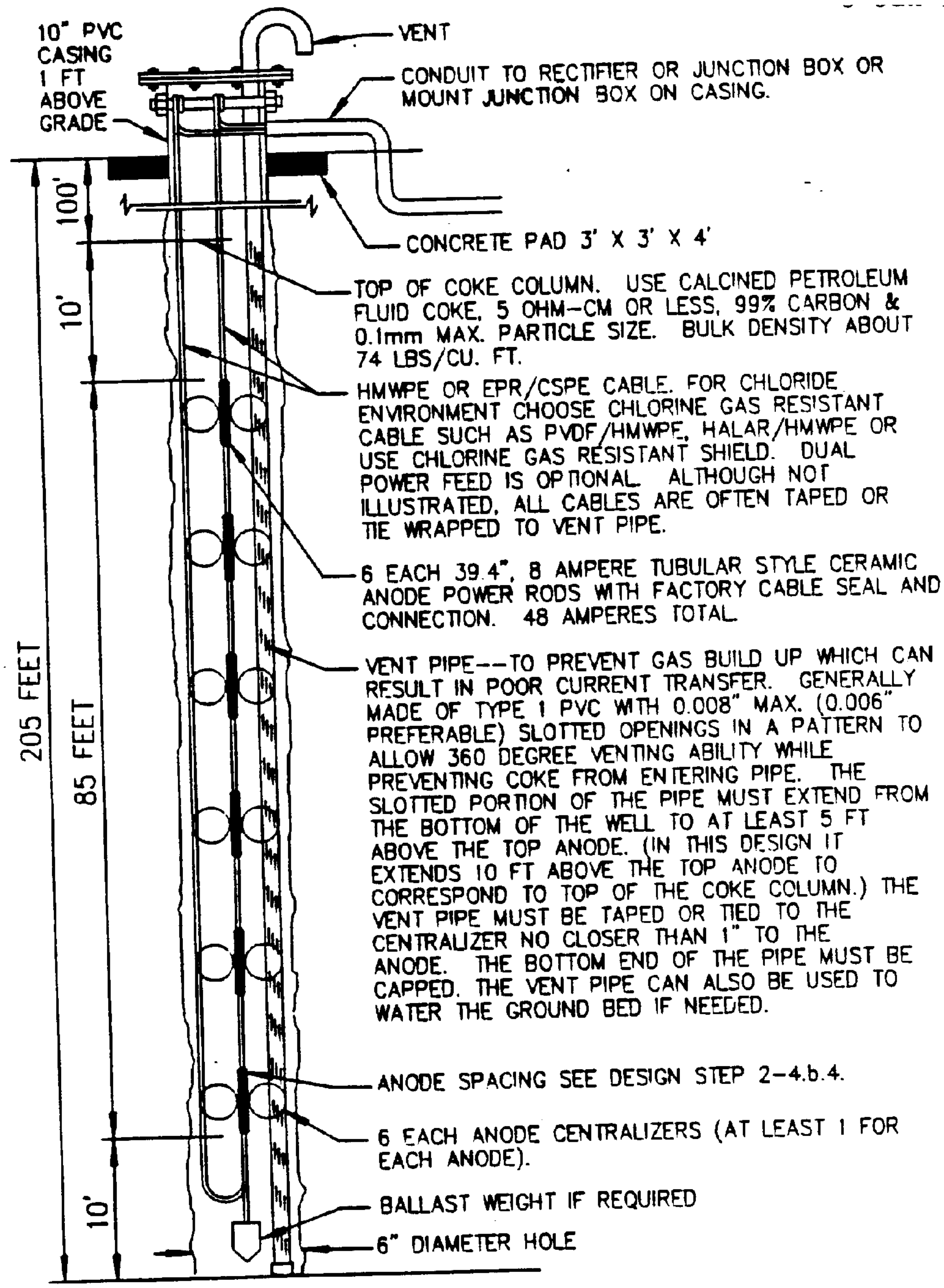


Figure 2-13 Ceramic Anode Tubular Power Rod Used in Deep Anode Bed

2-6. Elevated Water Tank (Ice Is Expected).

Impressed current cathodic protection is designed for an elevated water tank (figure 2-14). The tank is already built and current requirement tests have been done. Anodes must not be suspended from the tank roof because heavy ice (up to 2 ft thick) covers the water surface during winter. The anode cables could not tolerate this weight, so another type of support must be used. An internally supported hoop shaped wire anode system is selected.

a. Design data.

1) Tank is a pedestal supported spheroid with a 10-in. riser pipe. Only the bowl will be protected because the riser pipe is less than 30 inches in diameter. For riser pipes see section 2-7.

2) Tank dimensions are:

Capacity = 400,000 gal
Diameter of bowl = 51 ft 6 in.
High water depth = 35 ft
Height of bowl above ground = 100 ft

3) Water resistivity is 2000 ohm-cm.

4) Design cathodic protection anodes for a 15-year life.

5) Wire type ceramic anode will be used.

6) Wetted surfaces are uncoated.

7) Area above high water level is kept well coated.

8) Tank is subject to freezing.

9) The cathodic protection circuit resistance must not exceed 2 ohms.

10) The available electrical power is 120/240 V AC, single phase.

11) Based on structure current requirement testing recently performed on this tank, the current required for adequate cathodic protection is 25 amp. This high current requirement indicates that the tank internal coating is severely deteriorated.

b. Computations.

1) Calculate the length of wire in ft (LB) needed for the current required from a modification of equation 1-2:

$$L_B = \frac{I}{I_A}$$

where:

I = 25 amp (Current requirement from adequate cathodic protection from item 11 of paragraph 2-6a)

I_A = Allowable amp per ft of anode wire (varies depending on desired anode life and diameter), found in table A-3.

Select 0.0625-in. diameter copper cored anode wire based on the current requirement of 25 amp, 81 ft of anode wire will be required to provide an anode life of 15 years.

	Length of Wire	Anode Ring Diameter (D_R)
For 0.0625 in. $L_B = \frac{25}{0.31} =$	81 ft	25 ft 9 in.

2) Calculate the desired diameter of the anode wire ring (D_B). Experience shows that the diameter of the anode wire ring should be between 40 and 70 percent of the bowl diameter. For this example, use a hoop diameter equal to 40 percent of the tank bowl diameter:

$$D_R = 51.5 \text{ ft} \times 40\% = 20.5 \text{ ft}$$

3) Select anode wire:

Prior to calculating the circuit resistance of the anode wire ring, it must first be checked to determine if the length is adequate for the desired anode life. For an anode ring diameter of 20.5 ft, the circumference is 20.5 x B = 64.4 ft. This length is inadequate for the 0.0625-in. wire (which requires a minimum of 81 ft to meet the desired anode life). Therefore, we will increase the hoop diameter by 10 percent to 50 percent of the tank diameter:

$$D_R = 51.5 \times 50\% = 25.75 \text{ ft}$$

But this diameter provides an anode length that is still slightly less than that required for a 15-year mode life. Therefore, we will use a hoop diameter that is 55 percent of the bowl diameter:

$$D_E = 51.5 \times 55\% = 28.3 \text{ ft}$$

4) Calculate the anode-to-water resistance (R_A) for a 0.0625-in. diameter anode wire using equation 1-14:

$$R_A = \frac{0.0016\, p}{D_R} \left(1n \frac{8\, D_R}{D_A} + 1n \frac{2\, D_R}{H}\right)$$

Where:

p = 2000 ohm-cm (Water resistivity from item 3 of paragraph 2-6a)

D_R = 28.3 ft (Anode ring diameter from step 2 of paragraph 2-6b)

D_A = 0.00521 ft (0.0625 in)(Diameter of anode determined in step 3 of paragraph 2-6b)

H = 21 ft (Anode depth below water surface.) (Anode depth determined from the following calculations).

The anode depth below the high water line is approximately 60 percent of the distance between the high water line and the bottom of the tank. Water depth = 35 ft, cf. design data section 2-6a.

Calculate R_A:

$$R_A = \frac{0.0016\ (2000)}{28.3} \left[\ln \frac{8 \times 28.3}{0.00521} + \ln \frac{2 \times 28.3}{21}\right]$$

$$R_A = 0.113\ [\ln 43{,}455 + \ln 2.70]$$

$$R_A = 0.113\ (10.68 + 0.99)$$

$$R_A = 1.32 \text{ ohms}$$

This is within the design limitation of 2.0 ohms.

5) Determine the total circuit resistance (R_T), from equation 1-3:

$$R_T = R_N + R_W + R_C$$

Where:

R_N = Anode-to-water resistance
R_W = Wire resistance
R_C = Tank-to-water resistance.

a) Anode-to-water resistance (R_N) = 1.32 ohms from step 4 above. ($R_N = R_A$ since R_A is equal to one continuous wire anode).

b) Header cable/wire resistance (R_W) is solved using equation 1-15:

$$R_W = \frac{L_W\ R_{MFT}}{1000\ ft}$$

Where:

L_W = 115 ft (Effective wire length. The positive wires from the rectifier to each end of the anode circle will be approximately 115 ft long)

R_{MFT} = 0.51 ohm (Effective wire resistance per 1000 lin ft. Since there are positive wires from the rectifier to each end of the anode circle, each wire will carry about one half of the current [12.5 amp]. The wires selected are No. 10 AWG. Because the two wires are in parallel, the effective resistance is one half the single wire resistance [1.02 ohms per 1000 lin ft/2 = 0.51 ohm])

$$R_W = \frac{115\ ft \times 0.51\ ohm}{1000\ ft}$$

$$R_W = 0.06\ ohm$$

c) Tank-to-water resistance (R_C) and negative circuit resistance.

The negative wire is connected to the tank structure near the rectifier, so its resistance is negligible. The tank-to-water resistance is also negligible because the coating is very deteriorated.

d) Calculate R_T:

$R_T = 1.32 + 0.06 + 0.00$

$R_T = 1.38$ ohms

This is well below the design requirement.

6) Calculate rectifier voltage (V_{REC}) from equation 1-17:

$$V_{REC} = (I)\ (RT)\ (120\%)$$

Where:

I = 25 amp (Current requirement from step 11, paragraph 2-6a)

R_T = 1.38 ohms (Total circuit resistance from previous calculation)

120% = Rectifier voltage capacity design safety factor

V_{REC} = 25 amp x 1.38 ohms x 1.2

V_{REC} = 41.4 V

c. Select rectifier.

Based on the design requirements of 41.4 V and 25 amp, a commercially available 48-V, 28-amp unit is selected. To prevent over- or under-protection as the water level varies, automatic potential control is specified. The tank-to-water potential is maintained by the controller through two permanent copper-copper sulfate reference electrodes suspended beneath the anode wire circle. The reference electrodes should have a life of at least 5 years. The tank-to-water potential measured by the controller should be free of IR drop error.

d. Installation.

Figure 2-14 shows a typical installation while figure 2-14A provides a typical detail for a pressure entrance fitting for underwater power and reference cell wire penetrations.

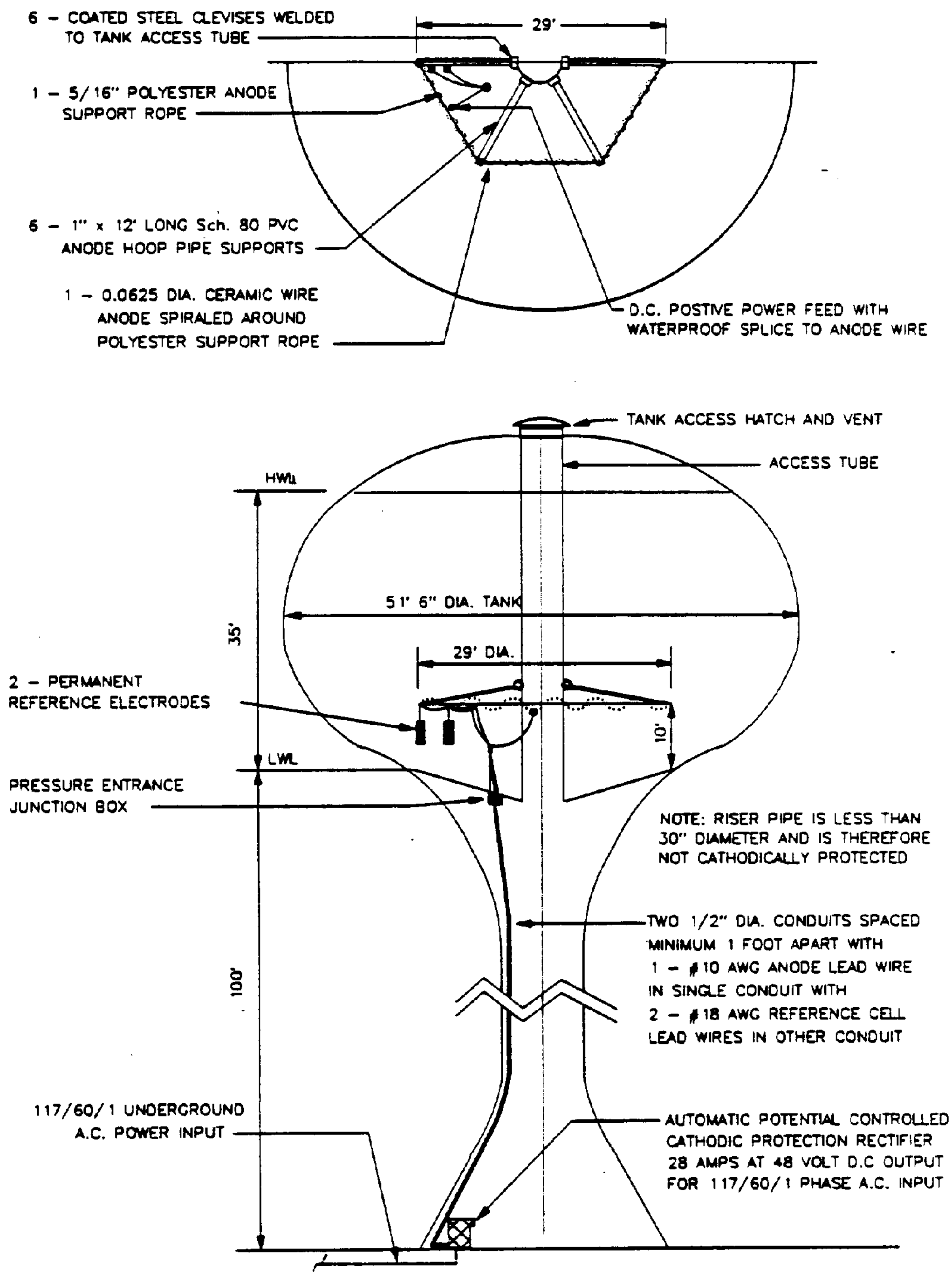


Figure 2-14 Elevated Pedestal Tank (Icing Conditions) With Hoop Ceramic Anode

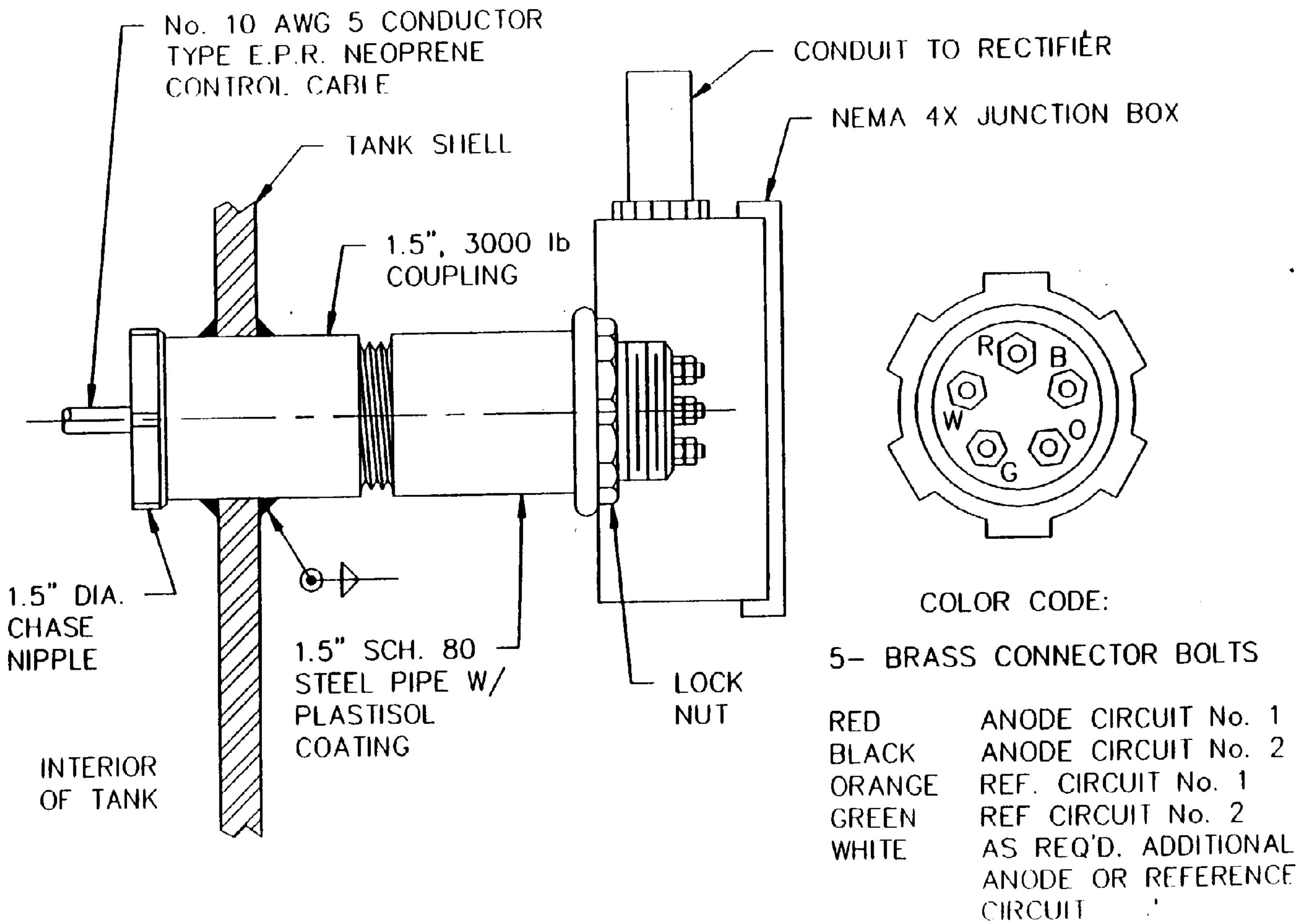


Figure 2-14A A Pressure Entrance Fitting for Underwater Power and Reference Cell Wire Penetrations in Water Storage Tanks

2-7. Elevated Water Tank (No Icing Will Occur).

This impressed current design is for a tank (figure 2-15) that has not been built; thus, it is not possible to measure current requirements and other factors. Calculated estimates are used.

a. Design data.

1) Tank will be ellipsoidal on both top and bottom.

2) Tank dimensions will be:

Capacity = 500,000 gal
Diameter = 56 ft
Tank height (from ground to bottom of bowl) = 115 ft
Overall tank depth = 39 ft
Vertical shell height = 11 ft
High water level = 35 ft
Riser pipe diameter = 5 ft

3) Water resistivity is 4000 ohm-cm.

4) Design for a 20-year life.

5) The tank water will not be subjected to freezing.

6) Segmented rod anodes will be used; 4-ft long by 0.138-in. diameter. Note: Segmented rods have an advantage in that they can be field assembled using factory-made connections. On the other hand, continuous wire (.0625-in. diameter) is also available in long lengths (typically 500 ft). These can be fabricated with factory-made wire connections but their overall length must be specified. Continuous wire will almost always be less expensive.

7) All wetted inner surfaces will be uncoated. Area above water will be coated.

8) Electric power available will be 120/240 V AC, single phase.

9) Design for a current requirement of 2.5 A per sq ft for the bowl and 8.0 A per sq ft for the riser. Due to the velocity of the water in the riser, the riser's current requirement is typically much higher than the bowl.

b. Computations.

1) Find the area of wetted surface or tank bowl (A) shown in figure 2-16 from equation 2-1:

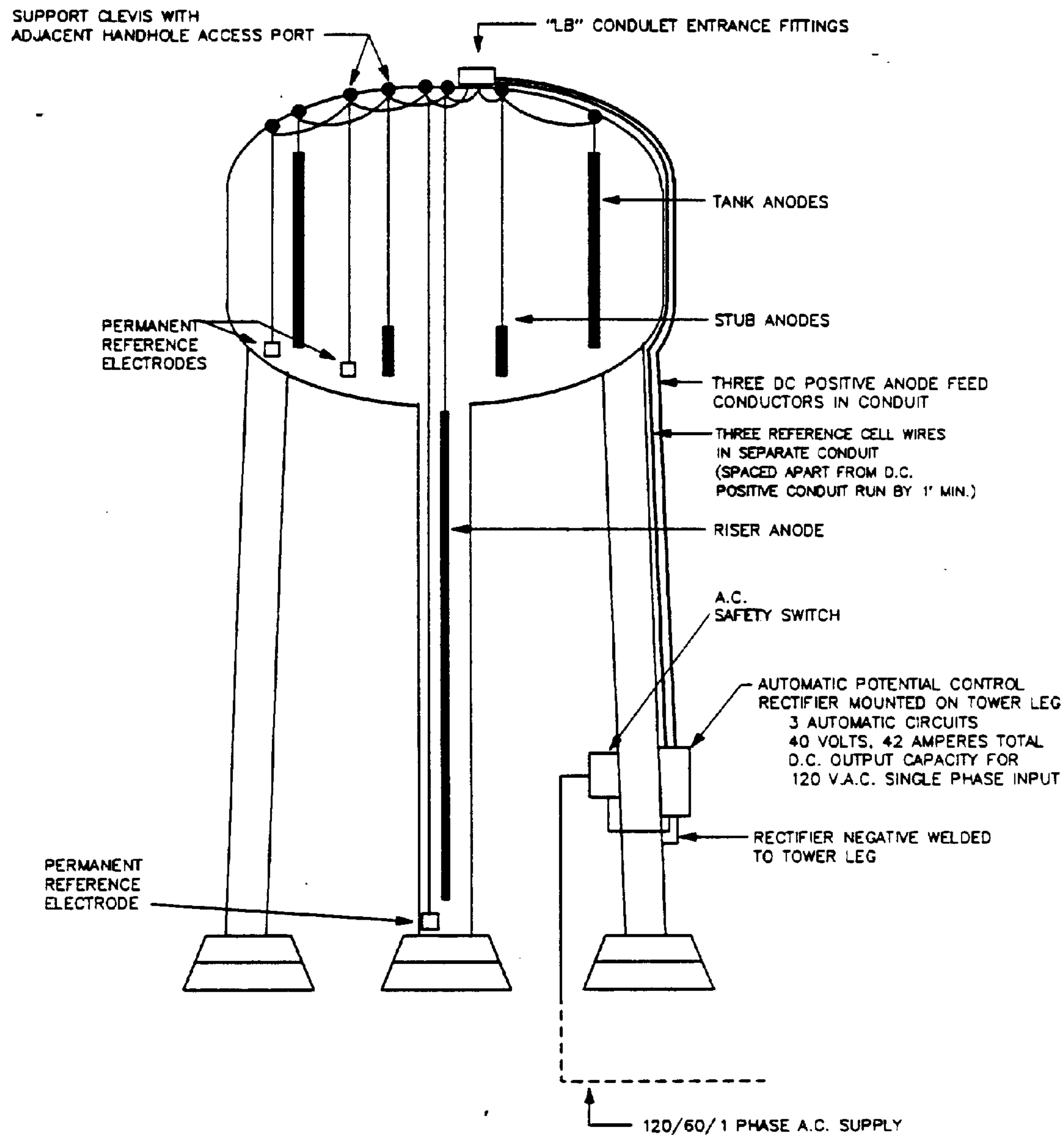


Figure 2-15 Elevated Water Tank Showing Rectifier and Anode Arrangement

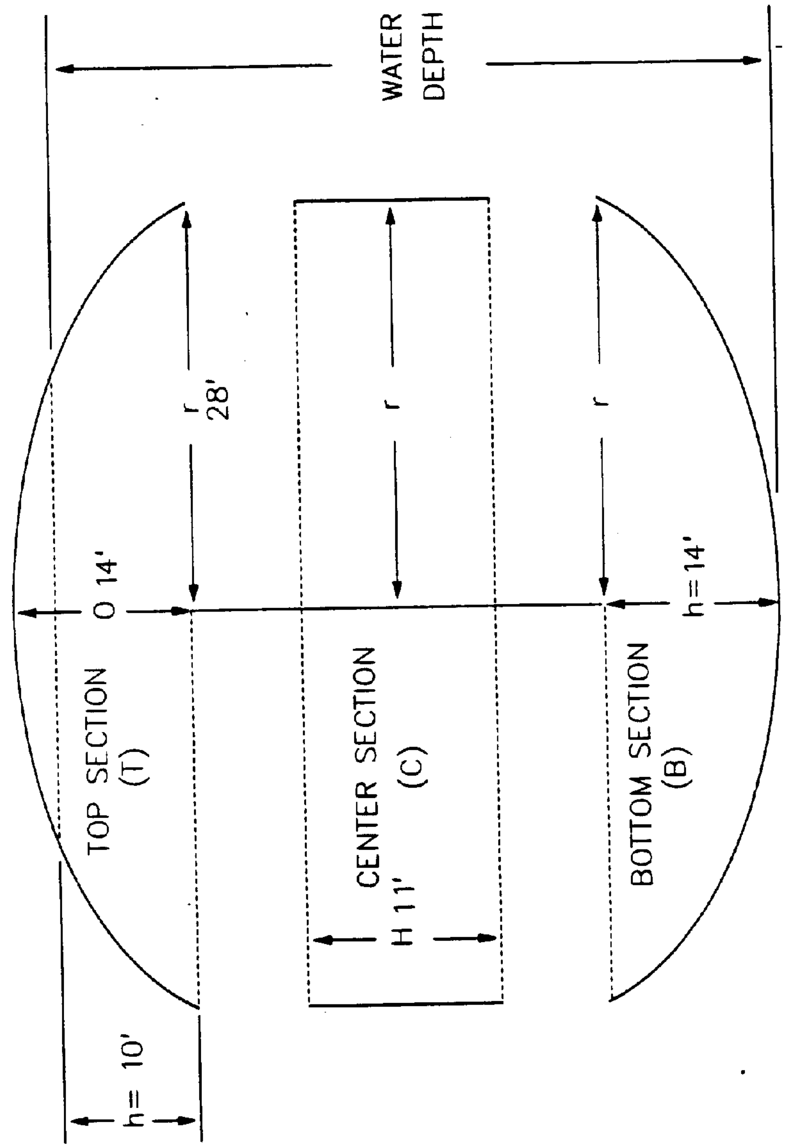


Figure 2-16 Segmented Elevated Tank for Area Calculations

$$A = A_T + A_C + A_B \qquad \text{(eq 2-1)}$$

Where:

A_T = Wetted area of the top section
A_C = Area of the center section
A_B = Area of the bottom section.

a) Find the appropriate wetted area of the top section (A_T) using equation 2-2:

$$A_T = 2\ B\ rh \qquad \text{(eq 2-2)}$$

Where:
r = 28 ft (Tank radius)
h = 10 ft (Water height)

A_T = 2 x 3.1416 x 28 ft x 10 ft

A = 1759 sq ft (approximate).

b) Find the wetted area of the center section (A_C) using equation 2-2:

$$A_C = 2\ B\ rh \qquad \text{(eq 2-2)}$$

r = 28 ft (Tank radius
h = 11 ft (Water height)

A_C = 2 x 3.1416 x 28 ft x 11 ft

A = 1935 sq ft

c) Find the wetted area of the bottom section (A_B) from equation 2-3:

$$A_B = \sqrt{2} \times A \times r \times \sqrt{h^2 + r^2} \qquad \text{(eq 2-3)}$$

Where:
r = 28 ft (Tank radius)
h = 14 ft (Water height)

$$A_B = \sqrt{2} \times 3.1416 \times 28 \times \sqrt{(14)^2 + (28)^2}$$

A_B = 3894 sq ft

d) Calculate (A):

A = 1759 sq ft + 1935 sq ft + 3894 sq ft
A = 7588 sq ft

2) Find the riser pipe area (A_R) using equation 2-2:

$$A_R = 2\ B\ r_R\ h_R \qquad \text{(eq 2-2)}$$

Where:
r_R = 2.5 ft (Riser radius)
h_R = 115 ft (Height of riser)

A_R = 2 x 3.1416 x 2.5 ft x 115 ft

A_R = 1806 sq ft

3) Find the maximum design current for the tank bowl (I_T) using equation 1-1:

$$I_T = (A)\ (I')\ (1.0 - C_E)$$

Where:
A = 7588 sq ft (Total wetted area of tankbowl from step 1 of paragraph 2-7b)
I' = 2/5 mA/sq ft (Required current density from item 9 of paragraph 2-7a)
C_E = 0.0 (Coating efficiency, wetted inner surfaces will be uncoated, from item 7 of paragraph 2-7a)
I_T = 7588 sq ft x 2.5 mA/sq ft x (1.0 - 0.0).

I_T = 18,970 mA; use 19.0 amp

4) Find the maximum design current for the riser (I_R),using equation 1-1:)

$$I_R = (A_R)\ (I')\ (1.0 - C_E)$$

Where:
A_R = 1806 sq ft (Total surface area of riser pipe from step 2 of paragraph 2-7b)

I' = 8.0 mA/sq ft (Required current density for riser pipe from item 9 of paragraph 2-7a)

C_E = 0.0 (Coating efficiency. Inner surfaces will be uncoated, from item 7 of paragraph 2-7a)

I_R = 1806 sq ft x 8.0 mA/sq ft x (1.0 - 0.0).

I_R = 14,448 mA; use 14.5 amp.

5) Select the number of anodes required for the bowl, to meet the anode system's 20-year design life using equation 1-2:

$$N = \frac{I}{I_A}$$

Where:

I = 19 amp (Current requirement determined in step 3)

I_A = 1 amp/anode (Current rating per anode from table 3-3 for 4-ft long by 0.138-in. diameter ceramic rods)

$$N = \frac{19}{1}$$

N = 19 rod segments (4-ft long segment)

6) Select the number of anodes required for the riser to meet the anode system's 20 year design life using equation 1-2:

$$N = \frac{I}{I_A}$$

Where:

I = 14.5 amp (Current requirement determined in step 4)

I_A = 1 amp/anode (Current rating per anode from table 3-3 for 4 ft long by 0.138-in. diameter ceramic rods)

$$N = \frac{14.5}{1}$$

N = 14.5; use 15 rod segments (4 ft. long)

7) Calculate the radius of the main anode circle (AR), using equation 2-4:

$$A_R = \frac{D \times N}{2\,(A + N)} \qquad \text{(eq 2-4)}$$

Where:

D = 56 ft (Tank diameter, from item 2 of paragraph 2-7a)

N = 10 anode strings (assumed: it is necessary to assume a number of anode strings since there are two unknowns in this equation.

$$A_R = \frac{56 \text{ ft} \times 10}{2\,(3.1416 + 10)}$$

$$A_R = \frac{560 \text{ ft}}{26.28}$$

A_R = 21.3 ft; use 22 ft for the main anode circle radius

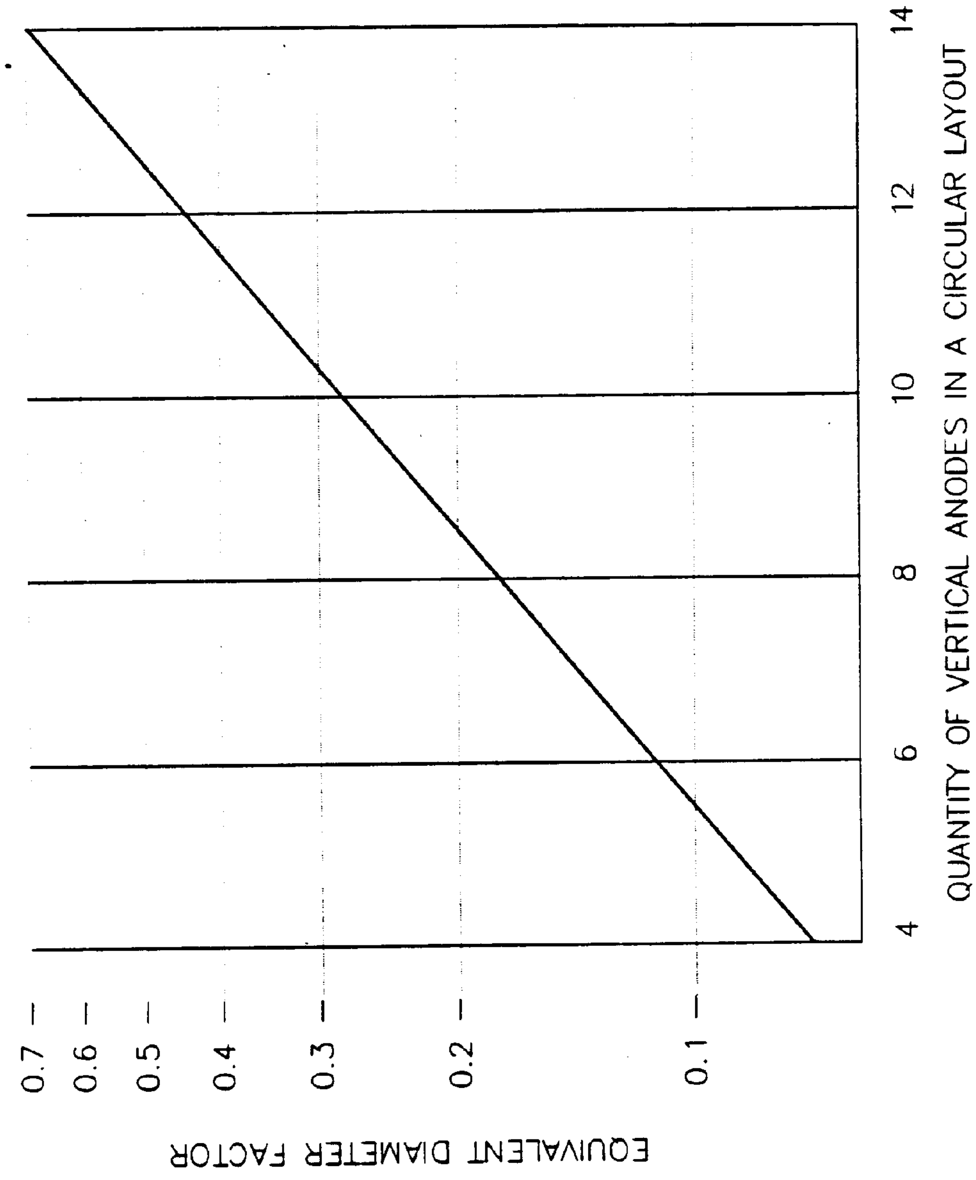
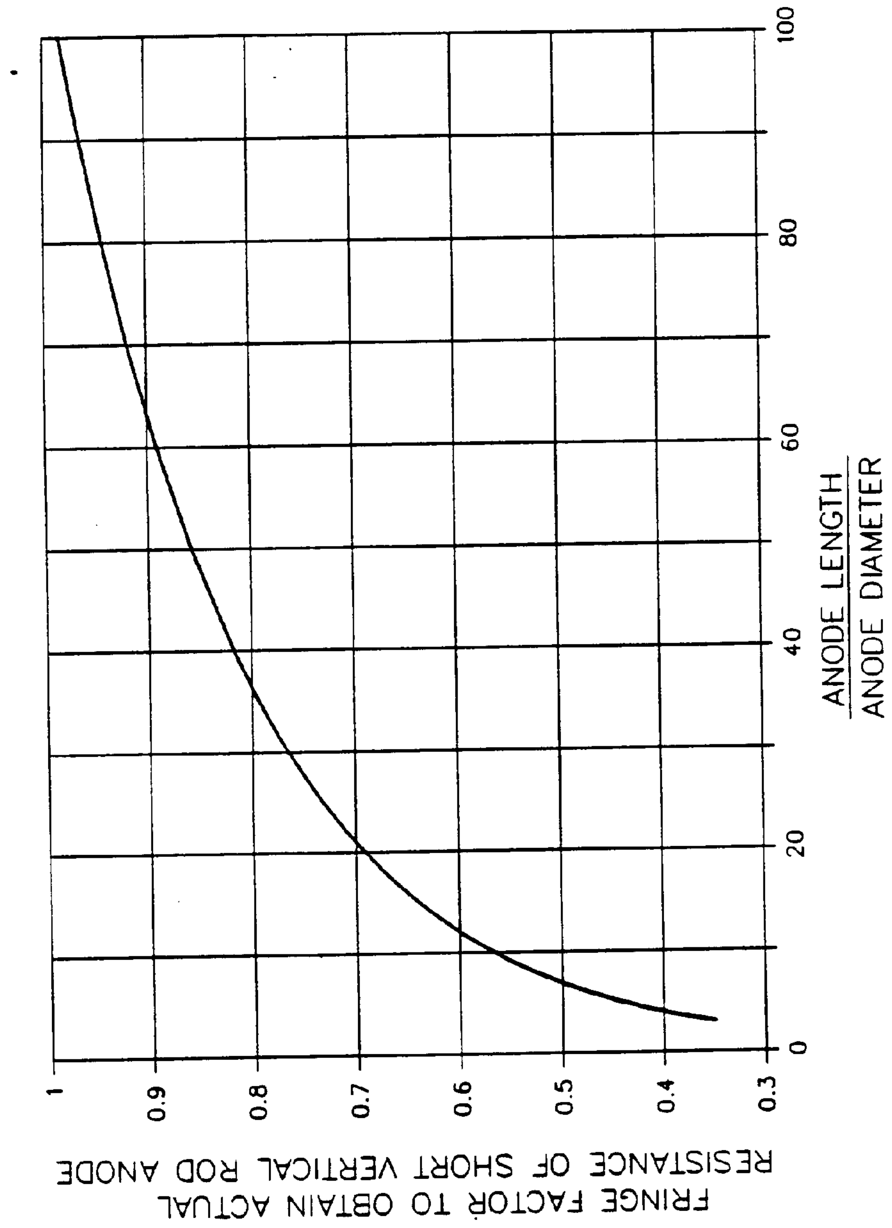


Figure 2-17 Equivalent Diameter Factor for Anodes in a Circle in a Water Tank



TO CALCULATE THE ACTUAL RESISTANCE OF A SHORT ANODE (L/D < 100)
MULTIPLY THE CALCULATED RESISTANCE BY THE FRINGE FACTOR
PROVIDED BY THIS CHART

Figure 2-18 Fringe Factor for Stub Anodes

8) Determine the center-to-center spacing (Cc) for the main anode strings.

a) To find circumference spacing (C_C), use equation 2-5:

$$C_C = \frac{2 \pi A_R}{N} \qquad \text{(eq 2-5)}$$

Where:

A_R = 22 ft (Radius of main anode circle from previous calculation.

N = 10 anode strings ([Assumed] Used in previous calculation)

$$C_C = \frac{2 \times 3.1416 \times 22 \text{ ft}}{10}$$

C_C = 13.8 ft; use 14 ft for center-to-center spacing between anode strings.

b) The cord spacing is approximately the same as circumferential spacing; 14 ft will be used (figure 2-19).

9) Select main anode system

Number of 4-ft long rod segments needed for the current requirement (from step 5) = 19. Number of anode strings utilized (from step 7) = 10. Using two rod segments per string will provide twenty anodes, which is sufficient for the current requirement. However, for rod type anode designs, the main anode rods should extend from a distance of 4 ft above the tank bottom to within 4 ft of the HWL. Due to the curvature of the tank bottom, the total water depth at the location of the main anodes is approximately 30 ft. Therefore, the minimum rod length should be 22 ft (30 ft - 4 ft - 4 ft = 22 ft). Since these rods come in 4 ft lengths, we will use six segments per anode with a total length of 24 ft.

10) Calculate the resistance of the main anodes to water (R_N) using equation 1-13:

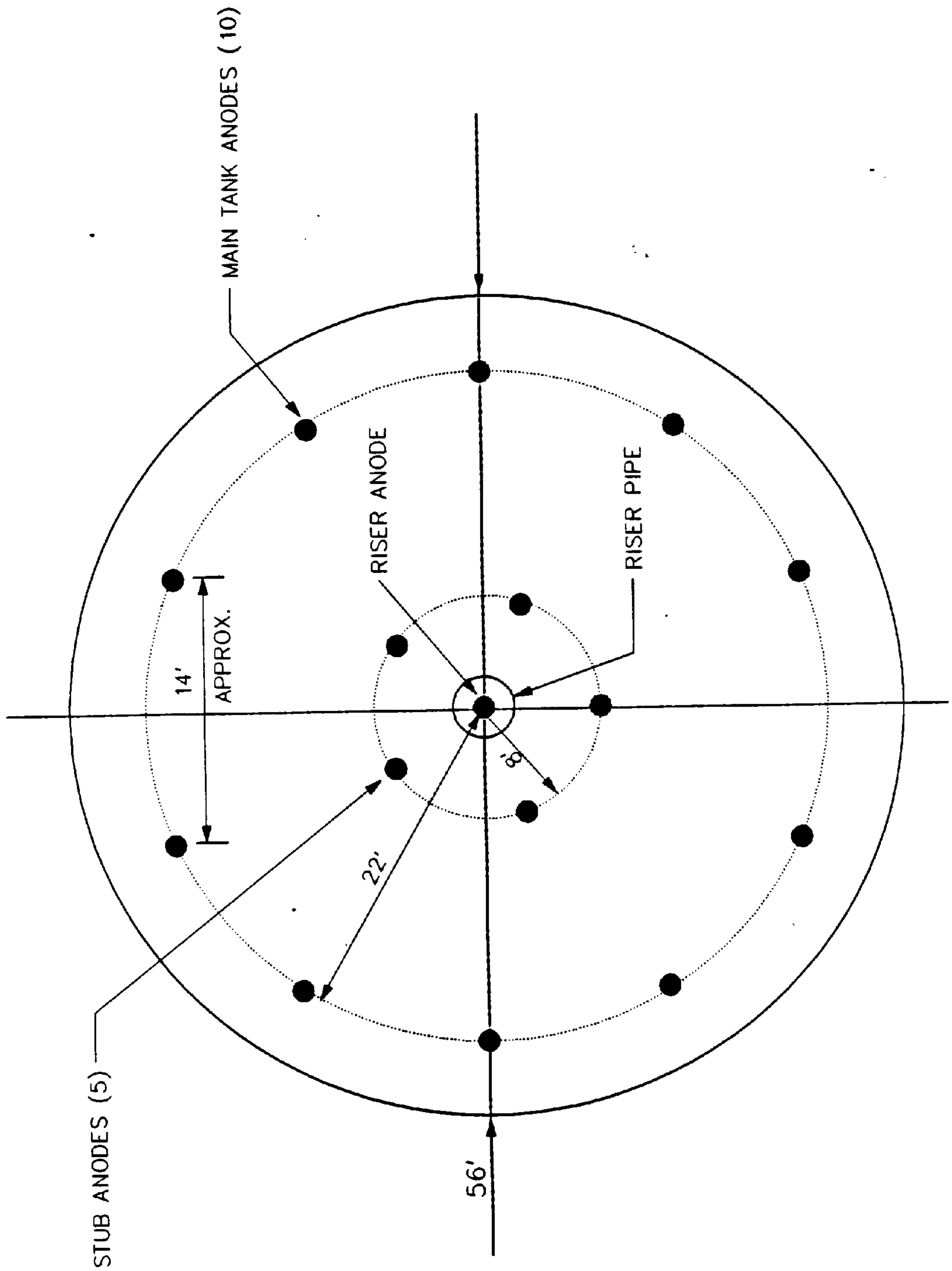


Figure 2-19 Anode Spacing for Elevated Steel Water Tanks

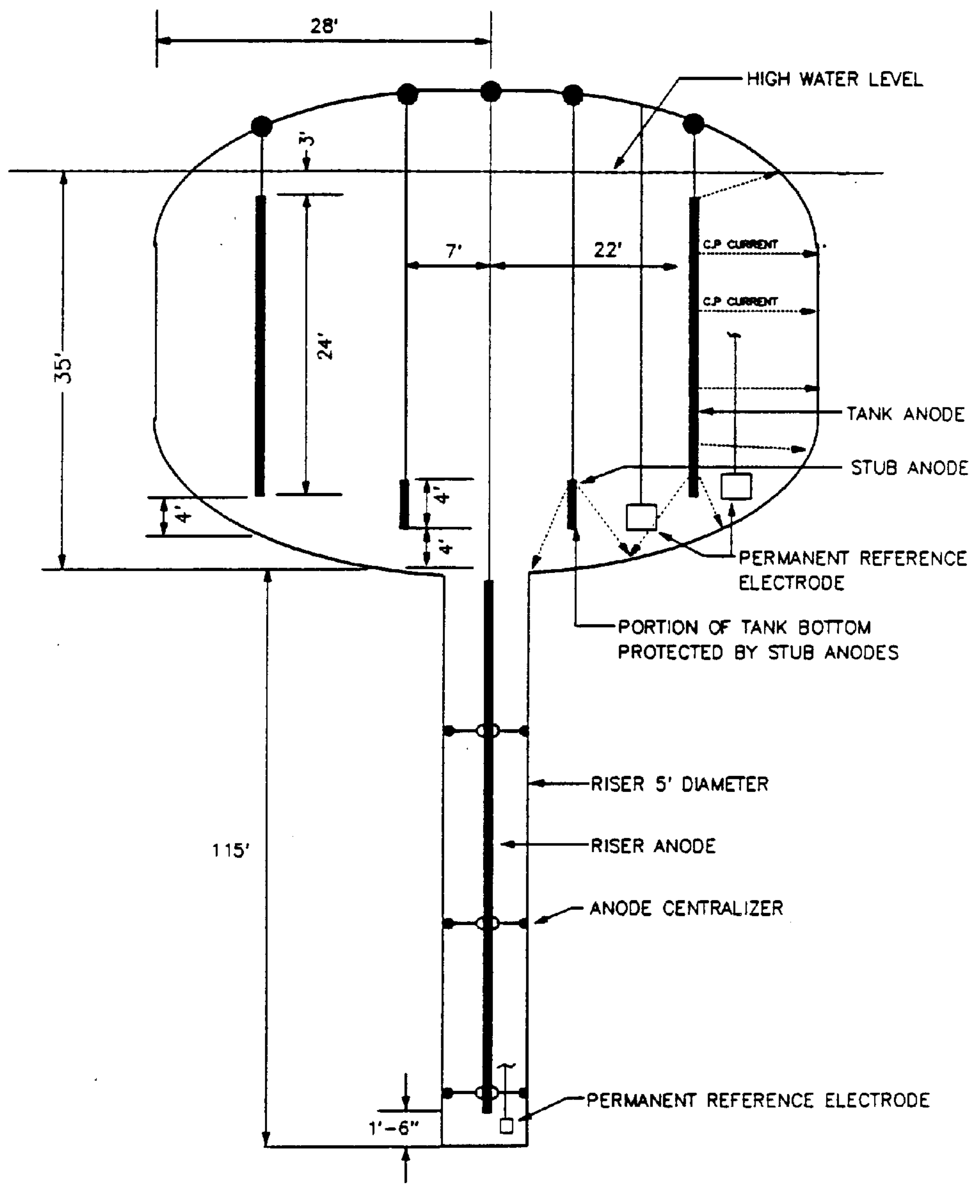


Figure 2-20 Anode Suspension Arrangement for Elevated Steel Water Tank

$$R_N = \frac{0.0052 \times p \times 1n\,[D/(2\ A_R \times D_E)]}{L_B}$$

Where:

p = 4000 ohm-cm (Water resistivity from item 3 of paragraph 2-7a)

D = 56 ft (Tank diameter from item 2 of paragraph 2-7a)

A_R = 22 ft (Radius of main anode circle from step 7 of paragraph 2-7b)

D_E = 0.275 (Equivalent diameter factor from figure 2-17)

L_B = 24 ft (Length of each anode from step 9 of paragraph 2-7b)

$R_N = \frac{0.0052 \times 4000 \times \ln(56/(44 \times 0.275))}{24}$

R_N = 1.33 ohms.

If the anode rod length-to-diameter ratio (L/d) is less than 100, the anode-to-water resistance needs to be adjusted by the fringe factor. (See step 12 for a discussion of fringe factor.)

In this case, L = 24 ft and d = 0.0115 ft. L/d, therefore, is (24/0.0115) = 2086. No fringe factor correction is required.

11) Calculate the stub anode requirement (N_S):

a) The main anode radius has been calculated to be 22 ft. The main anodes are spaced to provide approximately the same distance from the sides and the bottom of the tank. The main anode will protect a length inward along the tank bottom equal to approximately the same spacing that the anode is spaced away from the tank wall.

b) The anode suspension arrangement for the tank being considered is shown in figure 2-20. It can be seen that stub anodes are required for this design. For a two-ring anode design (main and one-stub anode ring), which is usually sufficient for tanks up to 1 million gal storage capacity, the 4-ft long stub anodes are located on a radius one-fourth of the bowl radius, or 7 ft (28 ft x 0.25 = 7 ft). Typically, there will be about one half as many stub anodes (two ring design) as there are main anodes so we will plan for five 4-ft long stub anodes on a 7-ft radius. The outside radius of the area to be protected by the stub anodes is approximately 13 ft and the inside radius is 2.5 ft (riser radius). The stub anodes are thus located on an 7-ft radius to place them in the center of the area to be protected. (Note: For smaller diameter tanks, stub anodes may not be required.)

c) Find the current division between main and stub anodes.

(1) The area of tank bottom protected by stub anodes (As) is found by equation 2-6 (see figure 2-20):

$$A_{SB} = B\ (r_2^2 - r_1^2) \qquad \text{(eq 2-6)}$$

Where:

r_1 = 2.5 ft (Riser radius)

r_2 = 13 ft (Radius of protected segment.) This is based on the fact that the main anode string is 6 ft from the tank wall and that the anode will protect another 9 ft (1.5 x 6 ft in toward the center on the tank bottom due to arc shape of the tank bottom). Outside radius of the area to be protected by the stub anodes is, therefore:

28 ft (tank radius) - 6 ft - 9 ft = 13 ft

A_{SB} = 3.1416 [(13 ft)^2 - (2.5 ft)^2]

A_{SB} = 3.1416 x 162.75

A_{SB} = 511.3 sq ft; use 512 sq ft as the area to be protected by the stub anodes.

(2) The current requirements for stub anodes is, therefore;

512 sq ft x 2.5 mA/sq ft = 1280 mA or 1.3 amp

(3) The total current requirement for the bowl is 19.0 amp (from step 3).

(4) The current for the main anodes is, therefore;

19.0 amp - 1.3 amp = 17.7 amp

d) Select number of stub anodes (N_S).

In step 11, five stub anodes were assumed. Check the number required from equation 1-2:

$$N_S = \frac{I}{I_A}$$

Where:

I = 1.3 amp (Current requirement from previous calculation)

I_A = 1 amp/anode current rating per anode from table 2-4 for 4-ft long by 0.138-in. diameter ceramic rods.

$$N_5 = \frac{1.3}{1}$$

N_S = 1.3; use 2 - 4 ft anode rods

The five anodes selected to provide proper coverage over the bottom are more than sufficient for the desired anode life.

12) Calculate the stub anodes-to-water resistance (R_N).

Find the stub anode resistance from equation 1-13:

$$R_N = \frac{0.0052 \times p \times 1n\,[D/(2\,A_R \times D_E)]}{L_B}$$

Where:

p = 4000 ohm-cm (Water resistivity from item 3 of paragraph 2-7a)

D = 56 ft (Tank diameter from item 2 of paragraph 2-7a)

A_R = 7 ft (Radius of stub anode circle from step lib of paragraph 2-7b)

D_E = 0.07 (Equivalent diameter factor from figure 2-17)

L_B = 4 ft (Length of each stub anode)

$$R_N = \frac{0.0052 \times 4000 \times \ln [56/(14 \times 0.07)]}{4}$$

R_N = 21.03 ohms.

Because the stub anodes are short, their anode-to-water resistance may have to be adjusted by the fringe factor. The fringe factor depends on the ratio of length-to-diameter (L/d). If L/d is less than 100, obtain the fringe factor from figure 2-18. Multiply the calculated stub anode-to-water resistance by the fringe factor (F) to obtain the adjusted resistance (R_{ADJ}).

$$R_{ADJ} = R_N \times F \qquad \text{(eq 2-7)}$$

Where:

R_N = Stub anode-to-water resistance from step 12.

F = Fringe factor from figure 2-18.

In this example, L/d for the stub anodes is:

L = 4 ft

$$d = 0.0115 \text{ ft}$$

$$L/d = \frac{4}{0.0115} = 348$$

In this case L/d is greater than 100, 50 no fringe factor correction is required.

13) Determine total resistance of main and stub anodes (R_T) from equation 1-3:

$$R_T = R_N + R_W + R_C$$

Where:
R_N = Anode-to-water resistance.
R_W = Header cable/wire resistance.
R_C = Tank-to-water resistances.

a) Main anode rods:

R_N = 1.33 ohms (from step 10)

R_W = 0.13 ohm

Header cable/wire resistance is calculated from equation 1-15:

$$R_W = \frac{L_W \, R_{MFT}}{1000 \text{ ft}}$$

Where:
L_W = 200 ft (After reviewing figure 2-20, it is estimated that 200 ft of wire will be required to connect the rectifier to the anode distribution wiring at the top of the tank)

R_{MFT} = 0.640 ohm (Wire resistance per 1000 lin ft of No. 8 AWG HMWPE insulated wire)

$$R_W = \frac{200 \text{ ft} \times 0.640 \text{ ohm}}{1000 \text{ ft}} = 0.13 \text{ ohm}$$

R_C = 0.0 ohm (Resistance of the tank-to-water and negative wire is negligible)

b) Calculate the total resistance of the main anode rods circuit (R_T):

$R_T = 1.33 + 0.13 + 0.0$

R_T = 1.46 ohms for main anodes.

c) Calculate the total resistance of the stub anode rods circuit (R_T):

Where:
R_N = 21.03 ohms (from step 12)
R_W = 0.13 ohm (same as main anode header)
R_C = 0.0 ohm (negligible)

$R_T = 21.03 + 0.13 + 0.0$

R_T = 21.16 ohms for stub anodes.

14) Design riser anode.

a) Current requirement = 14.5 amp (from step 4)

b) Number of anode rods required from step 6 = 15 rod segments (4-ft long each)

c) Select riser anode system.

For proper current distribution in the riser pipe, the anode units should not be placed too far apart. It is generally considered that each anode unit protects a length along the riser pipe equal to 1 ½ times the spacing of the anode from the riser pipe wall plus the length of the anode. The length of riser protected by one 4-ft long anode located 2.5 ft from the riser wall is therefore:

$$(2.5 \times 1.5) + 4 = 7.75 \text{ ft}$$

Number of anode required for a 115-ft riser:

$$N = \frac{115}{7.75} = 14.8 \text{ or } 15 \text{ anodes}$$

The number of anodes required for current distribution equals the number needed for the current requirement. To allow for a factor of safety, use twenty anodes.

d) Determine anode spacing.

Total riser length = 115 ft
Distance from bottom of riser to bottom of bottom anode = 1.5 ft
Space consumed by anodes = 20 anodes x 4 ft each = 80 ft
Total space consumed = 80 + 1.5 = 81.5 ft
Space remaining = 115 - 81.5 = 33.5 ft

For twenty anodes, there are nineteen spaces

$$\text{Spacing} = \frac{33.5}{19} = 1.76 \text{ ft or } 1 \text{ ft } 9 \text{ in.}$$

Such an assembly is possible since anode rod segments can be connected together with wire. Since the anodes are spaced so close together, it is better to use one long anode. Such an anode has less flexibility than the disjointed cable connected string, so there is less chance of its vibrating or being damaged by water turbulence.

For one long anode made of 4-ft segments screwed together, the number of anodes required is:

115 ft - 1.5 ft (distance from bottom) = 113.5 ft

$$\frac{113.5}{4} = 28.4 \text{ anodes}$$

Use 28 anode segments to keep the top segment within the riser.

Total anode length = 28 anodes x 4 ft/anode = 112 ft.

Weight of the anode string will be:

2.4 oz/anode x 28 anodes = 67.2 oz = 4.2 lb

Weight is not a factor in supporting the string.

15) Calculate the anode-to-water resistance of a single anode rod (RA), using equation 2-8:

$$R_A = \frac{0.0052\, p \,1n(D/D_A)}{L_B} \qquad \text{(eq 2-8)}$$

Where:

p = 4000 ohm-cm (Water resistivity from item 3 of paragraph 2-7a)

D = 5 ft (Riser diameter from item 2 of paragraph 2-7a)

DA = 0.0115 ft (0.138 in) (Diameter of anode rod from item 6 of paragraph 2-7a)

L_B = 112 ft (Length of anode rod from previous discussion)

$$R_A = \frac{0.0052 \times 4000 \times 1n\ (5./0.0115)}{112}$$

R_A = 1.13 ohms

16) Determine the total circuit resistance (R_T) of the riser anode, from equation 1-12:

$$R_T = R_A + R_W + R_C$$

Where:

R_A = Anode-to-water resistance of a single anode rod.

R_W = Wire resistance.

R_C = Tank-to-water resistance.

a) Anode-to-water resistance (R_A) = 1.13 ohms from step 15 of paragraph 2-7b.

b) Header cable/wire resistance (RN) from equation 1-15:

$$R_W = \frac{L_W\ R_{MFT}}{1000\ \text{ft}}$$

Where:

L_W = 240 ft (After reviewing figure 2-20, it is estimated that 240 ft of wire will be required to connect the rectifier to the riser anode string)

R_{MFT} = 0.640 ohm (Wire resistance per 1000 lin ft of No. 8 AWG HMWPE insulated wire)

$$R_W = \frac{240\ \text{ft} \times 0.640\ \text{ohm}}{1000\ \text{ft}} = 0.15\ \text{ohm}$$

Since this anode string is very long, the metal of the anode can represent a significant resistance. Since the current discharges all along the anode, one half of its length is used in the resistance calculation.

Manufacturer's data show the longitudinal resistance of a single 4-ft anode segment to be 0.053 ohm. Effective resistance of the string is:

$$\frac{0.053\ \text{ohm/anode} \times 28\ \text{anodes}}{2} = 0.74\ \text{ohm}$$

This resistance is very high compared to the anode resistance (greater than 10 percent) as a result, too much current will discharge near the top of the anode and not enough current will be discharged near the bottom of the anode. Therefore, either a double-end feed method will have to be used or copper-cored rods must be used. (Note: This is usually only a problem in fresh water applications when the anode rod length is greater than 30 ft.) In this case, we will elect to use copper cored 1/8-in. diameter rods. Manufacturer's data show the longitudinal resistance of a single 4-ft long copper-cored rod of this diameter is 0.0034 ohm. Effective resistance of this string is therefore:

$$\frac{0.0034\ \text{ohm/anode} \times 28\ \text{anodes}}{2} = 0.048\ \text{ohm}$$

Thus, the copper cored anode longitudinal resistance is less than 10 percent of the anode-to-water resistance (0.048 ohm/1.13 ohm - 0.043 = 4.3 percent) making this an acceptable riser anode design.

c) Tank-to-water resistance (R_C) and negative circuit resistance = 0.0 ohm.

d) Calculate total resistance of the riser circuit (R_T):

R_T = 1.13 + 0.15 + 0.0

R_T = 1.28 ohms for riser anode.

17) Calculate the rectifier voltage (V_{REC}) and current:

a) First, determine the voltage requirement (E) for each circuit using Ohm's Law:

$$E = I\ R_T$$

Where:
I = Current requirement.
R_T = Total circuit resistance.

Main Anodes:

I = 17.7 amp (from step 11c).
R_T = 1.46 ohms (from step 13b).

E = 17.7 x 1.46 = 25.8 V

Stub Anodes:

I = 1.3 amp (from step 11c).
R_T = 21.16 ohms (from step 13c).

E = 1.3 x 21.16 = 27.5 V

Riser Anodes:

I = 14.5 amp (from step 4)
R_T = 1.28 ohms (from step 16d)

E = 14.5 x 1.28 = 18.6 V

b) Summarize each circuit's resistance, current requirement and voltage requirement:

Circuit	Current (amp)	Resistance (ohm)	Voltage Required (V)
Main anodes	17.7	1.46	25.8
Stub anodes	1.3	21.16	27.5
Riser anodes	14.5	1.28	18.6
Total current requirement	33.5		

c) Determine the rectifier voltage (V_{REC}) based on the largest circuit voltage requirement of 27.5 V, because voltage requirement varies for all three circuits. With a 120 percent safety factor as in equation 1-17, the rectifier voltage is calculated:

$$27.5 \times (120\%) = 33 \text{ V}$$

Total current required = 33.5 amp.

c. Select rectifier

1) Rectifier capacity.

A commercially available rectifier having a rated output of 40 V, 42 amp is selected.

Because of the different circuit resistances, separate control of each circuit is required. This is best handled by a rectifier having three separate output circuits.

2) Automatic potential control

To prevent over or under protection as the water level varies, automatic potential control is specified. The tank and riser-to-water potentials are maintained by the controller through permanent copper-copper sulfate reference electrodes suspended within the bowl and riser. The reference electrodes should have a life of at least 15 years.

The automatic controller is located in the rectifier unit. The controller must be capable of sensing the potential accurately and free of IR (voltage) drop error. The control does this by turning off the rectifier for a fraction of a second, during which time the tank-to-water potential is measured. The measurement is then compared with a preset standard and the output adjusted accordingly.

d. Installation details.

Figures 2-19, 2-20, and 2-21 show typical details.

e. Guidelines for number of anode rings required.

The number of rings of anodes required varies with tank diameter. Table 3-7 gives suggestions.

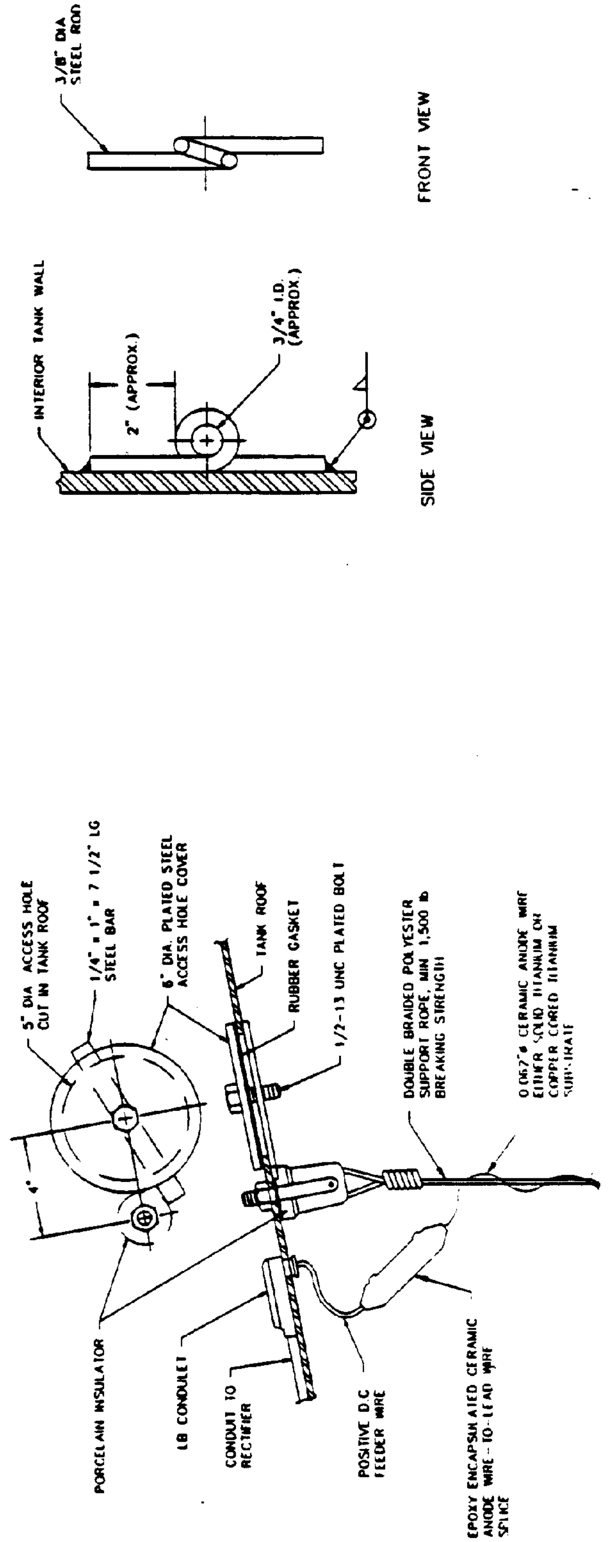


Figure 2-21 Water Tank Hand Hole Assembly for Roof-Supported Anodes and Support Bracket for Submerged Hoop Anodes

2-8. On-Grade Water Storage Reservoir (Ice Is Expected).

Impressed current cathodic protection is to be designed for the existing ground level water reservoir shown in figure 2-22. Coating is in poor condition and expected to deteriorate in the future. As the tank is not heated, ice forms in the winter. Current requirement tests have been made.

a. Design data.

1) Tank is cylindrical with a flat bottom.

2) Water resistivity is 2000 ohm-cm.

3) Tank dimensions are:

Capacity = 250,000 gal
Diameter of bowl = 46 ft
High water depth = 20 ft.

4) Design cathodic protection anodes for a 15-year life since tank will be repainted at that time.

5) Wire type ceramic anode will be used.

6) Design current density is 2.5 A per sq ft of tank area to be protected.

7) Wetted surfaces are poorly coated. As coating is expected to deteriorate, design for bare tank.

8) Area above high water level will be kept well coated.

9) Tank is subject to freezing and therefore a hoop type anode support system will be used.

10) Electrical power available is 120 V AC, single phase.

11) Current requirement at present for adequate cathodic protection is 9.0 amp.

b. Computations.

1) Find the area of the tank to be protected (A).

$$A = 2 B r h + B r^2$$

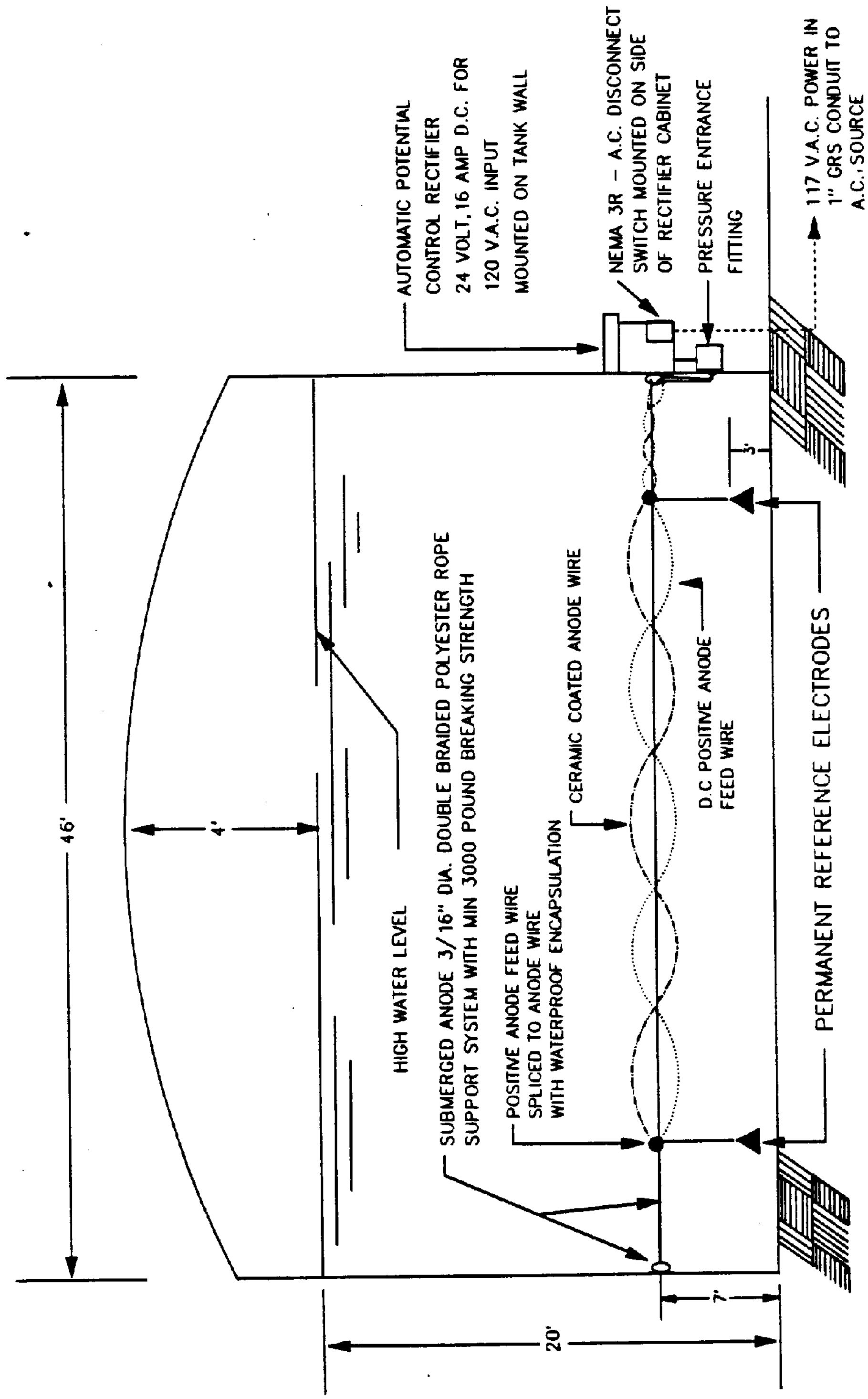


Figure 2-22 Submerged Cathodic Protection System for Ground-Level Water Storage Reservoir

Where:

r = 23 ft (Tank radius from item 3 of paragraph 2-8a)

h = 20 ft (High water depth from item 3 of paragraph 2-8a)

A = 2 it x 23 x 20 + it x 232

A = 2890 + 1662

A = 4552 sq ft

2) Compute the current requirement (I) using equation 1-11:

$$I = (A)(I')(l.0 - C_E)$$

Where:

A = 4552 sq ft (Area of tank to be protected from previous calculation)

I' = 2.5 mA/sq ft (Required current density from item 6 paragraph 2-8b)

C_E = 0.0 (Coating efficiency, assuming tank will eventually be essentially bare)

Current required:

I = 2.5 IDA/sq ft x 4552 sq ft

I = 11,380 IDA; use 12 amp

Since the computed 12 amp is larger than the tested requirement of 9 amp, use the 12 amp as the required current.

3) Calculate the length of anode wire in ft (L_B) needed for the current required, using a modification of equation 1-2:

$$LB = \frac{I}{I_A}$$

Where:

I = 12 amp (Current requirement from previous calculation)

I_A = Allowable amp per ft of anode wire (varies depending on desired anode life and diameter), found in table A-3.

Based on selecting a wire anode of 0.0625-in. diameter, the minimum wire length and hoop diameter can be calculated:

For 0.0625 in. $L_B = \frac{12\ \text{amp}}{0.31\ \text{amp/ft}}$

= 38.7 ft (Length of Wire for 15-Year Life) 12 ft 4 in (Minimum Diameter of Wire Circle)

4) Calculate the desired diameter of the anode wire circle (D_R). Experience shows that the diameter of the anode wire circle should be between 40 and 70 percent of the tank diameter for a cylindrical tank. In this case, we will try a hoop shape with a diameter equal to 60 percent of the bowl diameter:

D_R = 60% x 46 ft = 27.6 ft; use 27 ft 6 in

5) Calculate the anode anode-to-water resistance (R_A) from equation 1-14:

$$R_A = \frac{0.0016\,p}{D_R}\left(1n\,\frac{8\,D_R}{D_A} + 1n\,\frac{2\,D_R}{H}\right.$$

Where:

p = 2000 ohm-cm (Water resistivity from item 2 of paragraph 2-8a)

D_R = 27.5 ft (Anode ring diameter from previous calculation)

D_A = Assume 0.0052 ft (0.0625 in) (Diameter of anode wire from step 3 of paragraph 2-8b)

H = 12 ft (Anode depth below water surface) Anode depth has been determined from the following calculations:

The distance from the bottom of the tank to the anode wire circle should be about 40 percent of the water depth.

Water depth = 20 ft from item 3 of paragraph 2-8a.

20 ft x 40% = 8 ft

Anode depth below water surface (H):

H = 20 ft - 8 ft = 12 ft

Calculate R_A:

$$R_A = \frac{0.0016 \times 2000}{27.5} [\text{in } \frac{8 \times 27.5}{0.0052} + \text{in } \frac{2 \times 27.5}{12}]$$

$$R_A = 0.1164 [\ln 42{,}307.7 + \ln 4.6]$$

$$R_A = 0.1164 [10.65 + 1.531$$

$$R_A = 1.42 \text{ ohm}$$

At a current requirement of 12 amp, voltage required for this resistance, from Ohm's Law is:

$$E = I \times R_A$$

$$E = 12 \times 1.42 = 17.2 \text{ V}$$

This is a reasonable voltage, so the resistance of 1.42 ohms is acceptable.

6) Determine the total circuit resistance (R_T), from equation 1-3:

$$R_T = R_N + R_W + R_C$$

Where:
R_N = RA = Anode-to-water resistance.
R_W = Header cable/wire resistance.
R_C = Tank-to-water resistance.

a) Anode-to-water resistance = 1.42 ohms from step 5.

b) Header cable/wire resistance (R_W) from equation 1-15:

$$R_W = \frac{L_W \ R_{MFT}}{1000 \text{ ft}}$$

Where:

L_W = The positive wire from the rectifier to the first splice is 15 ft long. The power feed then continues on around the hoop to the opposite side. The length of this run is about 43.2 ft but since only half the current is passing through this portion, its effective length is 43.2/2 = 21.6 ft.

R_{MFT} = 1.02 ohms (From table 3-6, based on selecting No. 10 AWG cables)

$$R_W = \frac{(15 \text{ ft} + 21.6 \text{ ft}) \times 1.02 \text{ ohms}}{1000 \text{ ft}}$$

R_W = 0.037 ohm

c) Negative circuit and tank-to-water resistance (R_C).

The negative wire is connected to the tank structure near the rectifier, so its resistance is negligible. Tank-to-water resistance is also negligible.

d) Calculate R_T:

R_T = 1.42 + 0.037 + 0.00

R_T = 1.457 ohms; use 1.5 ohms

This is well below the design requirement.

7) Calculate the rectifier voltage (V_{REC}) from equation 1-17:

$$V_{REC} = (I)\ (R_T)\ (120\%)$$

Where:

I	=	12 amp (Current requirement from step 3)
R_T	=	1.5 ohms (Total circuit resistance from previous calculation)
120%	=	Rectifier voltage capacity design safety factor.

$$V_{REC} = 12 \text{ amp} \times 1.5 \text{ ohms} \times 1.2$$

$$V_{REC} = 21.6 \text{ V}$$

c. Select rectifier.

Based on the design requirements of 21.6 V and 12 amp, a commercially available 24-V 16-amp unit is selected.

d. Automatic potential control.

To prevent over- or under-protection as the water level varies, automatic potential control is specified. The tank and riser to water potential is maintained by the controller through permanent copper-copper sulfate reference electrodes suspended with the bowl and riser. The reference electrodes should have a design life of at least 15 years.

The automatic controller is located in the rectifier unit. The controller must be capable of sensing the potential accurately and must be free of IR (voltage) drop error. The controller does this by turning off the rectifier for a fraction of a second, during which time the tank-to-water potential is measured. The measurement is then compared with a present standard and the output adjusted accordingly.

e. Installation details.

Figures 2-22 and 2-23 show typical details.

f. Loop anode attachment guidelines.

The wire circle, or loop anode is supported from the sides of the tank by polyester rope as shown in figure 2-22. The number of supports varies with the tank diameter as recommended in table 3-8.

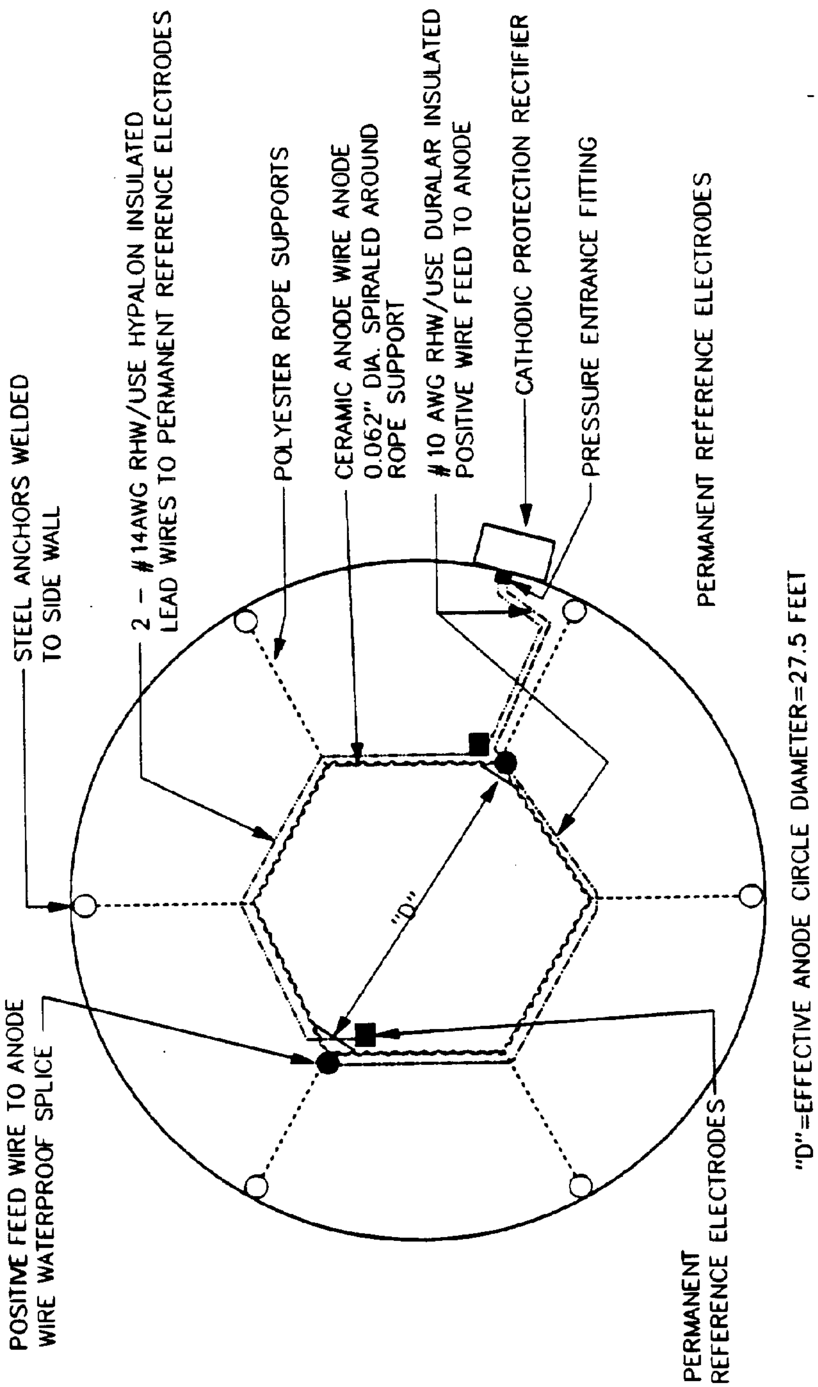


Figure 2-23 Details of Wire-type Anode System Designed To Withstand Icing Conditions Within Tank

2-9. Horizontal Anodes. (Underground Applications)

There are times when it is advantageous to install anode horizontally as shown in figure 2-24. For further information, see paragraphs 10.91 through 10.93 of TM 5-811-7 (reference 10). This configuration is particularly helpful when using packaged ceramic anodes (figure 2-24) since earth backfill can be solidly tamped around them. The anodes can be laid on the bottom of a trench or excavation with compacted backfill. This often achieves better compaction than when tamping in vertical holes. The design is undertaken in the same manner as described in Section 2-2 and 2-3. The single anode-to-earth resistance is calculated by using equation 2-11:

(eq 2-11)

Where:

RA = Anode-to-electrolyte resistance in ohms.
p = Electrolyte resistivity in ohm-cm.
L = Length of anode in ft.
d = Diameter of anode in ft.
h = Depth of anode in ft.

This equation is used to calculate the resistance of a single anode-to-earth.

For multiple anode installations, equation 1-11 may be used to approximate total resistance:

$$R_N = \frac{R_A}{N} + \frac{p\, P_F}{C_C}$$

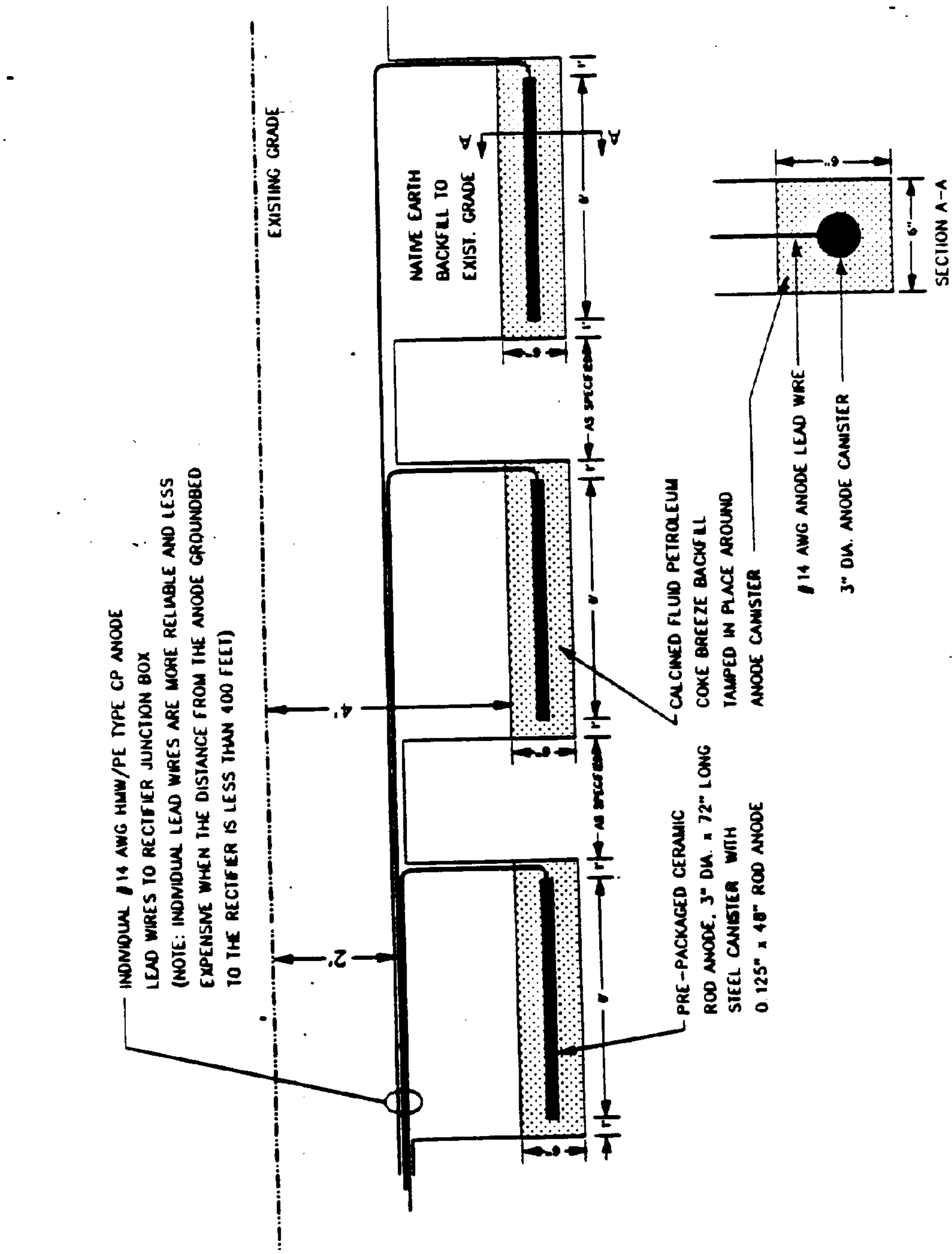


Figure 2-24 Horizontal Prepackaged Ceramic Rod Anode Groundbed

Where:

R_N = Resistance-to-electrolyte of "N" number of anodes

R_A = Resistance-to-electrolyte of a single horizontal anode

N = Number of anodes

p = Electrolyte resistivity in ohm-cm

P_F = Paralleling factor (table 3-5)

C_C = Spacing between anodes in ft. (The spacing between anodes is taken as the center-to-center distance between horizontal anode.)

As before, when equation 1-11 is applied to horizontal anodes, it yields approximate results. This is because the equation is based on vertical anodes. However, the results are sufficiently accurate for cathodic protection design.

2-10. Backfilling Packaged Anodes With Coke Breeze.

Although the calculations shown in Sections 2-2 and 2-3 assume that the packaged ceramic anodes will be buried directly in the earth, the accepted fail-safe design practice is to bury the packaged anode canister in a coke breeze backfill.

Backfilling the packaged anodes in coke breeze offers three advantages. First, it reduces anode-to-ground resistance. A typical example would be to backfill a 3-in. by 60-in. anode in a 8-in. diameter by 84-in. long coke breeze column. These dimensions, d = 0.66 ft and L = 7.0 ft, are then used in equation 2-8 or 2-10 to calculate resistance-to-earth.

The second advantage of using coke breeze backfill around packaged anodes is that coke breeze often results in better compaction then does soil. This also reduces anode-to-ground resistance and improves anode performance.

The most important reason, however, for backfilling these (as well as any other) prepackaged anode is that gas-blocking of the anodes will not occur. Gases (primarily oxygen) are released at the anode package surface. These can be entrapped by the soil at the anode package surface which can prevent further current discharge by the anode. The coke breeze provides a porous media through which these gases can migrate and dissipate preventing the possibility of gas blocking.